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EFFECTS OF MAINTENANCE ON SYSTEM RELIABILITY

SEPTEMBER 15, 1959

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A report under
Contract NObsr-64508

ARINC RESEARCH CORPORATION
A SUBSIDIARY OF AERONAUTICAL RADIO, INC.

ARINC

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EFFECTS OF MAINTENANCE ON SYSTEM RELIABILITY

September 15, 1959

A report under Military Contract NObsr-64508

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FOREWORD

The report submitted herewith summarizes the results of an investigation conducted for the military services by ARINC Research Corporation to determine the effects of maintenance on the reliability of electronic tubes and equipments. Initiated on the basis of tube studies sponsored by the Air Force, Army, and Navy under tri-service contract NObsr-52372, the investigation was carried out under the successor contract, NObsr-64508. These contracts have been administered for the services by the Bureau of Ships, Department of the Navy.

Field data analyzed in this report were collected by ARINC Research Corporation at the following locations: Carswell Air Force Base, Fort Worth, Texas; MacDill Air Force Base, Tampa, Florida; operations areas of Army European Command divisions stationed at Wurzburg and Bad Kreuznach, Germany; and the Norfolk Naval Air Station and Norfolk Naval Station, Norfolk, Virginia.

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SUMMARY

1. Purpose and Scope of Report

This report presents the results of a study conducted by ARINC Research Corporation to determine the effects of field maintenance of electronic equipment upon electron tube life and upon reliability of the equipment as affected by tubes. The study was designed to compare these effects among maintenance groups engaged in the repair of various types of equipments at Air Force, Army, and Navy bases. A further comparison of the effects of maintenance was made between these groups and groups of engineers or highly qualified electronics technicians. The latter groups furnished a standard against which to judge military maintenance; and, since the engineering groups were considered approximately equal in skills, they also provided a means for comparison of operational effects among the several military bases.

1.1 Basic Hypothesis

The principal question asked by the study was, "Does the military maintenance man remove tubes unnecessarily at repair; and, if he does, is it possible that because of a primary reliance upon tube replacement, more basic causes of equipment failure are left uncorrected to the extent that future reliability of the equipment is impaired?" An affirmative answer to both parts of this question would point to the need for a change in the approach to maintenance and would suggest the means whereby tubes might be conserved and equipment reliability simultaneously improved.

It would be essential, of course, to exercise caution in considering such changes, since, in a specific situation, other factors might make these changes impractical. For example, if tubes were a major source of trouble in some equipment types, mass tube removal as the first approach to repair might prove to be the quickest repair method in the majority of cases, even though each individual tube removal might not prove essential. Other approaches to repair in which the conservation of tubes is stressed might require more time in the repair process. If the time expended is of vital concern, then a different question must be posed, i. e., "Will the operating situation tolerate longer repair times for the possible gain in tube economy?"

1.2 Indices of Comparison

Since the efficiency of a maintenance group should not be judged as being either "good" or "bad" solely on the basis of quantity of tubes removed at repair, maintenance has been evaluated in this study on a much broader basis. Specifically, the following indices were selected for comparison of maintenance groups:

(1) Quantity of tubes removed -- both the total number and the number per repair action.

(2) Tube reliability function and mean time to tube removal.

(3) Proportion of repairs which involved equipment adjustments, tube replacements, and other part replacements.

(4) Time required to repair an equipment.

(5) Equipment reliability as measured by mean time between equipment repairs and/or between operator complaints.

The foregoing indices of maintenance were selected because they are believed to be measures of the skill of a maintenance group; and, as such, they furnish a basis for comparing differences in skill levels. The indices are also affected by other factors, including motivation, work loads, local base instructions, and work schedules.

In the ARINC Research Corporation study, the last-mentioned factors were generally more favorable to the engineers. In addition, the engineering groups obviously were influenced by instructions which they received to minimize tube replacements insofar as possible while maintaining the best possible equipment reliability. It is fairly evident that these instructions, to a great extent, determined the quantities of tubes which were removed by the engineers. No such directives were given to the military maintenance men. Thus, the conclusions to be drawn from the results of this experiment are more a measure of improvements which might be achieved with almost ideal maintenance than they are a true comparison of engineers and military maintenance personnel on the basis of skill alone. The end results are no less valuable, but when comparisons are made, care must be exercised to recall all of the factors in which differences occurred.

2. Major Conclusions

Major conclusions derived from the study are:

2.1 Between 50 and 70 percent of all tubes removed were unnecessary removals in the sense that the equipment would have continued to operate satisfactorily if they had not been removed. The quantity of tubes removed per repair was one of the most consistent differences noted in the comparison of engineering and military maintenance. The primary reason for the "unnecessary" removals appears to have been a combination of (1) poor correlation between tube testers and equipment-circuit requirements, and (2) tube-tester rejection limits which generally were overly stringent. This factor was less significant in the engineering maintenance because the engineers evaluated tube performance in the equipment socket first (according to instructions) and resorted to tube testers only as a secondary method of evaluation.

2.2 There is no apparent correlation between the quantities of tubes removed per repair (from different equipment types) and the number of tube sockets in the equipment. In those repairs which involved tube replacement, the number of tubes removed per repair averaged about 2.4 for military maintenance and 1.6 for engineering maintenance. This conclusion is consistent with the observation that a repair is generally localized to a small section of the equipment, and the tubes removed are from this section only.

2.3 The conclusions stated in Sections 2.1 and 2.2, above, and the distribution of the number of tubes removed per repair, are reasonably consistent with the hypothesis that logical trouble-shooting methods are followed to a certain point in the diagnostic process, and, thereafter, trial-and-error methods are substituted. The trial-and-error methods, combined with deficiencies in tube testers, account for many of the unnecessary tube removals.

2.4 The observed tube removal rates for military maintenance are fairly constant in time and thus exhibit an exponential-type reliability function. Unnecessary tube removals were minimized by engineering maintenance, and it is possible to detect the effect of tube deterioration in failure rates that increase with time. In this latter instance, the tube reliability functions approach the Gaussian or "normal" type with a considerably longer mean time-to-removal than that observed for military maintenance.

2.5 Military maintenance, in comparison with engineering maintenance, effected more equipment repairs by tube replacement alone and proportionately fewer by adjustment or other part replacements.

2.6 The average time required to repair an equipment at each base was shorter in nearly all instances for the engineering maintenance than for the military maintenance. On the average, the difference was approximately 30 percent.

2.7 Maintenance practices relating to tube testing and removal can readily obscure the true cause of equipment unreliability, since an equipment failure -- regardless of the cause -- is almost an invitation for military maintenance to remove tubes. Thus, in many cases, the situation may be one in which high tube removal rates result from poor reliability in the system design, rather than the converse -- i. e., that poor system reliability results from high tube failure rates. Extreme caution must be employed in assuming cause-and-effect relationships where maintenance emphasis is placed on tube testing as a means for repair.

2.8 Equipment reliability -- in terms either of time between repairs or of time between operator complaints -- shows no consistent differences whether maintained by military or engineering personnel. The difference in reliability for a given equipment type and a given type of maintenance between two bases is often greater than the difference attributable to the two classes of maintenance at a given base.

2.9 When the reliability of a given equipment type, maintained according to a given system of maintenance, is compared between bases, substantial agreement is obtained if the reliability is computed as a function of the number of missions. The agreement is no longer evident, however, if the reliability is computed as a function of elapsed operating time. The reason for the seemingly fundamental role of number of missions, as opposed to operating time, is unknown. The more obvious hypotheses -- such as cycling effects -- have been investigated on the basis of available data, with negative results; i. e., the hypotheses were rejected.

1. INTRODUCTION

The investigation which is the subject of this report stemmed from field studies of electron tube reliability conducted under Contracts NObsr-52372 and NObsr-64508 by the ARINC Reliability Research Department. These earlier studies raised various questions concerning the interpretation that should be placed on the data. If the field data could be taken at face value, the electron tube would have to be considered a very real barrier to future improvements in electronic reliability. There was substantial evidence, however, that other factors played an important role in tube performance. The evidence pointed particularly to maintenance of electronic equipments as a factor likely to have an adverse effect on both tube and equipment reliability. As a direct consequence of those indications, a field experiment was undertaken to determine what effect, if any, maintenance exerts upon electronic equipment reliability.

1.1 Observations Underlying the Study

Among the observations which raised the question of how properly to interpret field-collected electron tube data, the following were prominent:

(a) More than 30 percent of receiving tubes removed during repair by military technicians did not subsequently test defective.

(b) In many instances, multiple tube removals were made during a single repair. For example, 40 percent of all tubes removed during repair at one Air Force base were removed in clusters of two or more, and the majority of these clusters did not test defective.

(c) When the types of defects in the removed tubes were analyzed, it was observed that for any particular base there was a surprising similarity in the types of defects found, regardless of the type of equipment from which the tubes were removed; further, there was an equally surprising lack of agreement in defect patterns from base to base.

On the basis of such facts, several questions seemed pertinent: Was it possible that tube testers used in the field were inadequate for the purpose of isolating tube troubles? Were those tubes which did not test defective in reality the cause of equipment malfunction? It is known that some tube troubles are self-correcting -- for example, in certain applications of the type 6AR6 tube, the tube becomes gassy at elevated temperatures but, when the tube cools, the getter re-absorbs the gas. Phenomena of this type might account for some of the non-defective removals.

On the other hand, was it possible that the military technician was relying upon wholesale tube substitution as a means of repair? And was it also possible that he may not have been seriously concerned with whether or not the particular tube that had been removed was defective? Many first-hand observations of maintenance practices during equipment repair seemed to support both of these views.

The foregoing observations and unanswered questions clearly showed the importance of exercising great care in the interpretation of field tube data. It seemed essential at least to determine the proportion of total tube removals which were justified from the standpoint of equipment operation. The experiment that was initiated for the purpose of obtaining answers to the questions of interest is described in detail in Section 2 of this report. A few general observations relating to the study are appropriate, however, at this point.

1.2 Previous Maintainability Studies

Reliability studies in electronics have been in progress for over a decade. Many of the results have been published, and it is assumed their content is familiar to the reader. Studies of maintainability and maintenance techniques are more recent and perhaps less widely known. The major portion of recent work of this type has concerned itself with the problem of describing and interpreting the repair process. The objective has been to obtain knowledge which will facilitate selection and training of maintenance personnel. In the majority of instances, the investigations have been conducted under controlled conditions, by means of either actual equipment with built-in problems or simulated paper-and-pencil tests. The results of the studies vary somewhat, but there is general agreement on these points:

(a) Equipment repair cannot be assumed to be a routine task.

(b) The successful repairman has a greater knowledge of electronic facts and principles than h s the less successful repairman.

(c) The less successful repairman tends to drift into "dead ends" and has difficulty getting back on the right track.

(d) Successful repairmen make more use of test equipment.

(e) Aptitude tests which are being developed should be reasonably successful in predicting potential maintenance skill.

In several instances, the investigations referred to above were limited in scope to permit more detailed study of the various steps within the maintenance process. Moreover, since they were conducted in a laboratory environment, the results cannot readily be extrapolated to actual field operations.

The study described in this report, on the other hand, was broad in scope and was conducted in the field through the medium of maintenance personnel who were subjected to field environments and pressures. The broad scope was necessitated by the decision to measure maintenance effectiveness in terms of the reliability of parts and equipments as well as of maintenance effort. To avoid the risk of changing the maintenance environment by detailed interviews and discussion with the maintenance men, and thus producing non-representative results, reliance was placed upon engineering and statistical analyses of the end results. The major feature of the study is that it was an attempt to describe and analyze some of the interrelationships between men and machines under actual field conditions, on the basis of measurement of the effect of the man on the machine.

1.3 Organization of Report

This report is organized into four sections. Section 1, the Introduction, has stated some of the questions and problems in the fields of reliability and maintainability which form a background for the study.

Section 2 provides information on the detailed objectives, the experimental design and the conditions under which the experiment was performed. The statement of conditions is necessarily qualitative, since adequate measures of maintenance environments have yet to be developed.

Section 3 is the presentation of data. Because the data would otherwise become unduly repetitious, one equipment type -- the AN/ARC-27 UHF Transceiver -- has been used as the primary vehicle for the illustrative development of the analyses and conclusions. In certain cases, when it has seemed necessary for the development of the main thesis, data from other equipments have been included. It may be said generally, however, that the data from other equipment types substantiate the findings and conclusions concerning the AN/ARC-27 equipment.

The AN/ARC-27 was selected for the primary illustrative role for the following reasons:

(a) The equipment was in use at three different bases selected for the test and thus furnishes a good vehicle for comparison of the effects produced by the different operating bases upon maintainability and reliability.

(b) The equipment was in almost continuous operation during flight and thus accumulated many hours of operating time during the test period.

(c) The equipment required frequent repair and therefore was represented by a considerable quantity of failure and maintenance data.

Section 4 of the report presents a discussion of the major findings from the investigation and some recommendations applicable to maintenance which could lead to improved maintainability and reliability in military electronic equipments.

2. DESCRIPTION OF THE INVESTIGATION

In order to resolve some of the questions posed in the Introduction, ARINC Research Corporation -- with the cooperation of the Air Force, Army, and Navy -- planned and carried out, on an extensive scale, experiments and investigations described in the remainder of this section.

2.1 Hypotheses

The two major hypotheses which were to be tested were:

(a) That military maintenance technicians make unnecessary tube replacements in the course of equipment repair.

(b) That since tube replacement is commonly resorted to in attempting a repair, the possibility exists that (1) the real source of trouble is not eliminated, but is compensated for by the tube replacement, and (2) new troubles are engendered by excessive handling. Thus, if maintenance were to rely less upon tube replacement, equipment reliability would be improved.

In addition, two minor hypotheses were to be evaluated. These were:

(a) That in complex equipments -- where complexity is measured by the number of tube sockets -- one would find a higher rate of tube removal per socket.

(b) That a sizable proportion of the mechanically defective tubes become defective as a result of excessive handling.

The investigation was designed also to provide data on several indicators of the maintenance problem -- for example, the time required to repair equipments and the frequency of operator complaints.

2.2 Dimensions of the Field Study

For the purposes of the study, two classes of maintenance personnel were placed under surveillance. One class was made up of typical military maintenance personnel -- operating, insofar as possible, without knowledge of the purpose of the investigation. No attempt was made to influence this group, and the only request made was that they cooperate in collecting the required data. They were subjected to normal personnel turn-over, underwent the usual supply difficulties, and had access only to their normal repair facilities. In order to minimize the effect of the test itself on military maintenance procedures, the military technicians were informed that this was to be an ARINC Research Corporation tube evaluation study of the type in which they had previously participated.

The other maintenance group was composed of engineers or highly trained technicians. These personnel were responsible for the maintenance of the equipments assigned to them, and used only the type of maintenance facilities available to the military technicians. For the engineering group, the daily maintenance routine was not interrupted by additional duties, as it was for the military, although the engineers were assigned the added responsibility of keeping their own records. They were informed of the purpose of the test and were given the following instructions:

(a) Keep all tube replacements to a minimum insofar as possible.

(b) Within the limitations of the foregoing instruction, do whatever is feasible to maximize equipment reliability.

The test was conducted at four military installations, representing the Air Force, the Army, and the Navy. The equipment types selected for surveillance were typical of those at each installation. Both types of maintenance groups were represented at each installation, and both groups were responsible for the maintenance of the same types of equipment. Nearly all tubes placed under surveillance were newly installed in the equipments at the initiation of the test.

From the initiation to the termination of the field test -- a period of approximately 2 years -- the individual equipments in test accumulated between 300 and 15,000 hours of operating time, dependent upon their type, their use, and the base of operation.

Records were kept on each equipment and on each removed tube. The data recorded for the equipments included:

equipment operating time between operator complaints; time between repairs; types and quantities of parts removed; the maintenance man's description of the repair; where the equipment failure was detected (in flight, pre-flight, scheduled maintenance, etc.); time required to repair the equipment; time spent awaiting parts from supply; time spent in preventive maintenance; down-time on the vehicle due to equipment failure; number of men assisting at a particular repair; and information needed for equipment identification.

The data recorded for the tubes included the usual tube identification information, as well as information necessary to associate the tube with a specific equipment. The time of operation and the nature of the defect, if any, also were included.

At the termination of the test, all equipments -- including those maintained by the military -- were put into operating condition by the engineers, then each tube was removed from each equipment and tested on a tube tester. A complete record was kept of all tubes which were found to be defective at the time of this terminal check.

Nine different equipment types, approximately 400 individual equipments, and thousands of electron tubes were under surveillance during the test; and approximately 25 engineers and well over 100 military technicians were actively engaged in maintaining the equipments. Table 1 is a summary -- by test base -- of the types and quantities of equipments under surveillance during the field investigation.

2.3 The Maintenance Environment

It is generally recognized that native ability and experience (including training) are the two factors which primarily determine the success of a maintenance group. While the maintenance groups studied in this test undoubtedly differed with respect to these two characteristics, the observed variability in the data appears greater than can reasonably be explained by differences in ability and experience alone. Further, in some respects, the data are more nearly alike for the engineering and military maintenance groups at a particular base than for two engineering groups at different bases. This difference is particularly evident when a comparison of observed equipment reliability functions is made. The marked variability in the data from different bases suggests unique factors in existence at each base, and, in general, suggests that the data are materially affected by the environment in which the maintenance group operates.

TABLE 1

SURVEY OF EQUIPMENTS UNDER SURVEILLANCE DURING TEST

BASE	EQUIPMENT TYPE	EQUIPMENT FUNCTION	TYPE OF VEHICLE	NO. OF TUBES PER EQUIPMENT*	NUMBER OF EQUIPMENTS
Carswell Air Force Base, Fort Worth, Texas	AN/ARC-27	UHF Transceiver	B-36 Aircraft	55	10
	AN/ARN-14	Navigation(radio)	B-36 Aircraft	25	10
	K-System (K3)	Bombing/Navigation	B-36 Aircraft	233	10
MacDill Air Force Base, Tampa, Florida	AN/ARC-27	UHF Transceiver	B-47 Aircraft	55	10
	AN/ARN-14	Navigation(radio)	B-47 Aircraft	25	10
	K-System (K4)	Bombing/Navigation	B-47 Aircraft	237	10
Norfolk Naval Air Station, Norfolk, Virginia	AN/ARC-27	UHF Transceiver	AF-2S Aircraft S2F-1 Aircraft	55	10
	AN/APS-31 AN/APS-38	Radar-Navigation and Anti-Submarine	AF-2S Aircraft S2F-1 Aircraft	153 209	10 10
Norfolk Naval Station, Norfolk, Virginia	AN/URR-13	UHF Receiver	Aircraft Carrier	23	8
	TED-3	UHF Transmitter	Aircraft Carrier	16	8
Infantry Division, Wurzburg, Germany	AN/PRC-6	Handy Talkie	Portable Man-Carried	13	108
	AN/PRC-10	Walkie Talkie	Portable Man-Carried	11	108
Armored Division, Bad Kreuznach, Germany	AN/GRC-4 Set A	Transceiver	Medium Tank	30	96
	AN/GRC-4 Set B	Transceiver	Medium Tank	26	96

* Does not include tubes in sealed amplifiers, e.g., those in the AN/PRC-10; or tubes in certain sockets not under surveillance, e.g., two 3B28 sockets in the TED-3.

In this section, certain aspects of the maintenance environment will be discussed on the basis of the reported observations of ARINC Research field personnel. This discussion has been divided into three sections for ease of presentation. Section 2.3.1 describes the differences in attitudes of the engineering and military maintenance groups, and discusses the effect of these attitudes on the data. Section 2.3.2 is a discussion of the different maintenance organizations. This information is included not for the purpose of comparing Air Force, Army, and Navy maintenance organizations, but for the purpose of showing how the various groups have been tailored to suit the different tactical needs, and to suggest the manner in which the type of maintenance organization can affect both reliability and maintainability data. The third section, 2.3.3, discusses some of the interactions which were observed between the equipment operators and the maintenance men, and the effects of these interactions upon the data.

2.3.1 The Attitudes of the Maintenance Groups

A major difference between engineering and military maintenance may lie in their respective attitudes. In the following two subsections, group attitudes are discussed in a general manner; more specific comment on differences in attitudes appears in the discussion in Section 2.3.3 of the interactions between operators and maintenance groups.

2.3.1.1 The Engineers

It is believed the most important factors directing the engineers' maintenance practices during the test were the rules, prescribed by ARINC Research Corporation, by which the engineers were governed. These were, in brief: (a) minimize tube removals, and (b) maximize equipment reliability. It is questionable whether or not the results of the study would have been the same as they are if the engineers had not been given these rules. In fact, it could be questioned whether, in that event, the difference between engineering and military maintenance would have been appreciable.

It is interesting to note, however, that almost all of the engineers believed there was a basic incompatibility between the above-mentioned rules. The majority expressed the opinion that tubes were the major cause of equipment unreliability, and that while they could -- and would for the sake of this test -- keep tube removals to what they considered a minimum, they believed equipment reliability would have to suffer from this rule of action -- if not in the present, at least in the future.

One engineering group -- that at Norfolk Naval Air Station -- went so far as to reject the minimum-tube-removal requirement in favor of the criterion of maximum equipment reliability. This change was effected when they believed the point had been reached where certain types of tubes would begin to fail. Beginning at this point in the test, greater freedom was permitted in the removal of tubes, with the justification that this was a sound preventive-maintenance policy. The effect of the change in emphasis is interestingly demonstrated in the data. No other engineering group deliberately abandoned minimum tube replacement as a criterion. A possible explanation is that the equipments in the other groups with which a comparison can be made operated less time than did the equipments in the Norfolk Naval Air Station segment of the test. In these other groups, insufficient equipment operating time was accumulated to cause a serious tube wear-out problem.

It is believed the delegation to the engineers of responsibility for recording the data in their segment of the test materially influenced -- and altered with time -- the course of engineering repairs. Most important was the fact the engineers knew the past history of all their equipments. They not only knew the age of the equipment in hours -- and, therefore, the age of the tubes -- they also knew the types of equipment failures which had occurred in the past and what repair actions had been attempted. The engineers at the Norfolk Naval Air Station reached their decision to begin removing tubes as a preventive maintenance measure because of the information contained in their equipment records. It was also on the basis of these records that the engineers came to believe intermittent failures were a serious problem. The full extent of intermittent failures became evident only when past history of a specific equipment could be readily scanned for repeated operator complaints.

One other factor that may have actively shaped the attitude of the engineers, and one whose importance is difficult to measure, was the competitive nature of the test. They knew they were being compared with military maintenance and the desire to do a good job undoubtedly could have been strong. It is highly probable the engineers believed that because of their education and experience they were expected to prove themselves superior to the military.

In some instances, the engineers who performed the maintenance represented the company which had manufactured the equipment they maintained. These individuals could well have had the added incentive of making their company's equipment prove to be reliable.

Undoubtedly, other factors also had an effect. For example, most engineers expressed dissatisfaction with the adequacy of the field tube testers. Rather than rely entirely upon the tube tester, they would resort to substitution of a known good tube in the equipment to determine whether or not the tube was really the cause of the equipment malfunction. Another factor which may have had an effect was that the engineers, being entirely responsible for their individual equipments, would gain no particular advantage by delaying the repair; thus, generally, they made the repair as soon as possible.

2.3.1.2 The Military

The military technician's attitude regarding maintenance also is affected by many factors. He is subjected to pressures different from those that affected the engineers. Some of these pressures -- particularly the effects of the type of tactical operation -- will be discussed in Section 2.3.3.

The maintenance group's prime responsibility within the operational group is to keep vehicles (aircraft, ships, tanks, etc.) and their equipments in workable condition. If there is pressure of time, and a vehicle is badly needed, the simplest method by which the vehicle can be returned to service is by the substitution of a spare electronic equipment for the failed equipment. Among military maintenance organizations (with the exception of shipboard maintenance), achieving availability by this means is extremely common. The practice of substitution, however, tends to delay the repair of the failed equipment. It was observed during the ARINC Research investigation that the feeling of responsibility for individual equipments was not present to the same degree in military maintenance as it was in engineering maintenance. Often, in the military groups, several different men would work on the same equipment. This division of labor resulted in part from the procedure of leaving the repair to the next shift and in part from the echelon system of repair. The effect was that much repair work was repeated.

Pressure of time had another effect upon the attitude of the military maintenance man. When maintenance was seriously pressed, their first reaction in many cases was to resort to mass tube substitution. Such action may seem justifiable on the grounds that: (a) Tubes are easy to remove, and (b) tubes are frequently thought to be the most common cause of equipment failure. This viewpoint undoubtedly is based partially upon past experience, although in great degree responsibility must rest with the maintenance manuals and with the method of training, both of which actively encouraged tube replacement.

While observing the work of military maintenance men during this test, ARINC Research representatives noted that in many instances the technicians had difficulty in diagnosing causes of equipment malfunction. Often, they resorted to trial-and-error part substitution at the circuit level (at Norfolk Naval Air Station this was called the "Easter Egg" process of trouble isolation).

Most maintenance men, when questioned, readily admitted to a feeling of inadequacy for the task of repairing the equipments assigned to them, and many expressed a desire for more, formal training or at least for on-the-job training that could be supervised by the more experienced men. While some on-the-job training is provided, the problems of military reassignment and the loss of good men from the Services seriously hampers this program.

The effect of additional military duties on the maintenance job was reported from all surveillance bases as another factor influencing the technician's attitude. In the Services, a surprising amount of time is spent on non-maintenance activities. For example, it was observed during the investigation that because of routine shipboard duties, the time spent by the Navy technician on active maintenance was limited to between two and five hours a day.

2.3.2 The Organization of Maintenance

Military maintenance organizations usually are stratified into several levels of maintenance which generally correspond both to the skill of the personnel and to the degree of difficulty of the maintenance task. Three general levels of maintenance performed within the military structure are discussed in Sections 2.3.2.1 - 2.3.2.3.

2.3.2.1 First-Level* Maintenance

Usually, the least-skilled men are associated most closely with the operational use of the equipment -- in fact, the lowest level of maintenance may, in some instances, be performed by the equipment operator. Maintenance at this level normally is restricted to periodic checks of equipment performance, cleaning of the equipment, front panel adjustments, and removal and replacement of the larger units of the electronic system. The personnel at this level usually do

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* "Level" is equivalent to "echelon" in the Army.

not attempt to repair the failed units, but merely forward them to the next higher level of maintenance for repair. In the Army, the lowest level of maintenance -- designated as first- and/or second-echelon maintenance -- is performed either by the equipment operator or by the company repairman; and, in the Air Force, this first level of maintenance may be performed either by the crew in flight, or, if on the ground, by flight-line maintenance personnel. There is no apparent division of maintenance effort into formal repair levels in Naval aircraft maintenance; however, in practice, the least-skilled maintenance men generally perform a function similar to that of flight-line personnel in the Air Force. In Naval shipboard maintenance, also, there appears to be no stratification by maintenance skill; and, since the size of the maintenance group carried aboard a ship is necessarily limited, the individuals in the group are responsible for all types of assignments -- from the simple performance check to the most difficult of repairs.

2.3.2.2 Second-Level Maintenance

Military maintenance groups at the second level are generally more skilled and better equipped than those at the first level, and are charged with performing more detailed maintenance. At this level, failed units and equipments are repaired by replacement of sub-units and by replacement of piece-parts. The test equipment is better suited for the diagnosis of probable causes of equipment malfunction, and may include sufficient bench-test apparatus to permit testing of the operational performance of the equipment. Because of the amount of test equipment and spare parts required, a more permanent location is needed for second-level maintenance than for a first-level group. Second-level maintenance is generally able to provide equipment-repair support for several lower-level maintenance groups.

In the Army, the maintenance organization which most nearly corresponds to the second level of maintenance is the Signal Repair Team. There are two levels of maintenance in the Army between the company level and the Signal Repair Team -- i. e., battalion and regimental maintenance -- but, in practice, these two groups do little more than is accomplished at the company level. The major function performed by these intermediate groups is that of collecting failed equipments which cannot be repaired at the company level and transferring them to the Signal Repair Team. In the Air Force, the second level of maintenance is performed by the Armament and Electrical (A&E) shops; and, in the Navy, there is an airborne electronic shop maintenance group whose personnel also perform the flight-line maintenance. Naval

shipboard maintenance has a centrally located shop facility for repair of those equipments which cannot be repaired on the spot. The same personnel who work in the central shop facility also perform maintenance at the equipment locations.

2.3.2.3 Third-Level or Depot Maintenance

The third level of maintenance for all three Services is depot maintenance, which may be far-removed geographically from the base of operation and may perform services for several bases. At the maintenance depots, facilities are available for completely overhauling the equipments and for rebuilding them, if necessary. Depot maintenance was excluded from the ARINC Research Corporation test.

2.3.2.4 Organization of Engineering Groups In Test

The engineering maintenance groups under surveillance during this field investigation were not separated into different levels of maintenance as were the military groups. Insofar as possible, the engineering groups performed both first- and second-level maintenance. In the Army, the company repairmen were encouraged to turn in failed equipments to the engineer without first attempting a repair. The engineer performed all equipment maintenance which ordinarily would have been performed by the company, the battalion, the regiment, or the Signal Repair Team. Some of the equipments in the engineering segment of the Army test occasionally may have been repaired at the company level by the company repairman; and it is highly probable that if repairs of this type were performed, the records of the repairs were lost to the test data. The engineers assigned to the Air Force performed both flight-line and shop maintenance; however, it is assumed they were given some assistance by the military at the flight line. In the Naval Air segment of the test, it was originally intended that the engineers would supervise equipment repairs actually performed by the Navy technicians. This approach was soon abandoned, and the majority of the data represents maintenance work performed completely by the engineers. In the Navy Shipboard part of the test, the engineer performed all maintenance on the equipment assigned to him throughout the entire test.

In the selection of the form of organization for the engineering maintenance groups, the objective was not to organize them differently from the military organizations, but to provide them with the most efficient arrangement for maintaining adequate control of the entire maintenance

operation. The engineers were responsible for keeping detailed records on the equipments they maintained; and, as a result, they needed to be present at each repair action. Because of this record-keeping function, they had individual responsibility for the equipments, and a single engineer generally was responsible for the entire repair action.

2.3.2.5 Reasons for Stratification

Stratification by level of maintenance in the military is made essential by the demands for tactical deployment of the equipment, and it is also a solution to the problem of efficiently using maintenance men of varying skills. Periodic check-outs of electronic equipment require a major portion of maintenance time. However, this type of work normally does not require a high level of skill and may effectively be assigned to the less skilled men, thus releasing the more highly skilled men to perform the more difficult repair jobs. Unfortunately, in the military today, there is a shortage of skilled maintenance men, and this shortage is constantly aggravated by personnel turnover and by failure of the more skilled men to re-enlist. As a result, new men must continually be trained on the job.

The use of multiple maintenance levels has several consequences which must be considered as having a direct bearing upon the data collected in the investigation. Since in the military more than one man may be involved in a repair action -- for example, in the Air Force both flight-line and shop maintenance personnel may work on an equipment -- certain repairs must be treated as the work of two skill levels of maintenance. Not only may two skill levels be involved in a given repair, but different test equipment and facilities also may be used. This fact implies several conditions which must be weighed when engineering and military maintenance data are compared:

(a) It seems reasonable to expect the military to spend, on the average, somewhat more active time in the performance of repair work, because in the course of a single repair, some equipments will have to pass through two levels of maintenance (flight line maintenance and shop maintenance).

(b) Since there is undoubtedly some administrative delay in the transfer of equipments from one level of maintenance to the next, it should be expected that longer delays would be experienced before an equipment is returned to service.

(c) Military maintenance may perform more work on an equipment because second-level maintenance may redo or even undo some of the work performed at the first level.

(d) A difference in attitude toward the equipments and their repair may have developed because of differences in the extent of responsibility for equipment repair. The engineers generally were responsible for all repairs from the time the equipment failed until it was repaired and returned; the military personnel performed only those repairs that were assigned to them through a type of screening procedure. For example, in the Air Force, shop maintenance repaired only those equipments that could not be repaired by flight-line maintenance. The maintenance effort of a military technician thus was more selective -- more concerned with the nature of the repair than with the individual equipment. This difference in approach may have altered materially the nature of repair actions attempted by the military.

2.3.2.6 Effect of Tactical Demands on Maintenance Organization

The primary argument for stratification of maintenance into several different levels, each with a slightly different repair function, is based upon the tactical demands of the equipment. Each of the three Services makes different tactical use of its equipment, and the differences are reflected in the structure of the respective maintenance organizations.

Shipboard maintenance is an example of nonstratified military maintenance. Aboard ship, electronic equipments are in nearly continuous service for extended periods of time, and during these periods little maintenance support can be expected from outside the ship itself. Practically all repair facilities and manpower must be self-contained; and, because of space limitations, redundancy of personnel and equipment alike must be kept to a minimum. Since the equipment is in nearly continuous operation, most repairs have to be attempted at the point of equipment failure, and many difficult repair actions are performed that under other circumstances would not be attempted. The Navy's solution to the problems generated by these conditions has been to organize the maintenance group around a few well-trained technicians. These select few perform all equipment maintenance

and repair, except the minor functions which are performed by the operator of the equipment.

Within the Air Force, equipment requirements are determined by the mission of the aircraft. Generally, little repair is attempted during flight because (a) the crews cannot be spared too long from their other duties, and (b) only limited quantities of spare parts can be carried aboard the aircraft. Since space limitations prohibit redundancy of equipment, most maintenance is performed on the ground; and, because tactical demands require the potential for rapid repair of equipments on the ground to enable the aircraft to be returned to service quickly, the Air Force has attempted to solve the repair problem by establishing a flight-line maintenance group -- in addition to the shop-maintenance group. Flight-line maintenance is restricted to removal and replacement of the larger units of the electronic system. It is often performed under considerable pressure, while shop maintenance is somewhat more free from pressures and thus can undertake the more time-consuming repairs.

The Air Force has used the two-level system of maintenance advantageously. It was observed that, under the flight-line maintenance system, and with a redundancy of electronic units, aircraft availability is high. It was also noted, however, that considerable delay may occur before failed units are repaired in the shop and returned to service. (In the Navy, aircraft maintenance is not formally divided into flight-line and shop-maintenance groups; however, in practice, certain men tend always to perform the flight-line function while others restrict their activities to shop maintenance.)

In the Army, the equipment requirements necessitate a different approach to the repair problem. Each company has its individual repair unit and its own repairman; and because of the internal structure of the company, there is, in effect, a type of equipment redundancy. The use of the squad and platoon system within the company nearly precludes complete failure of communication, because if one group -- i.e., squad or platoon -- experiences communications failure, the other groups still will be able to provide communication for the company. Ordinarily, companies do not use equipment redundancy in the sense that extra equipments are held in readiness to be used when others fail; they are supplied with replacement equipments by the battalion or regimental maintenance organizations.

In the Army, equipments should be repaired at the place of failure by the company repairman whenever possible in order to achieve maximum company efficiency. However, there

are severe limitations on the types of repairs that can be performed in the field. The company repairman is restricted to the performance of minor repairs such as adjustments and some tube and battery replacements, because only limited numbers of spare parts can be carried into the field. The more difficult repairs must be made at higher echelons or when the company returns to garrison. The higher echelons of maintenance, which require less mobility than the companies, are able to stock larger quantities of spare parts and equipments and can maintain more elaborate repair facilities. The battalion, regiment, and Signal Repair Team are all capable of more detailed repair actions than the companies; however, in practice, the battalion and regimental maintenance personnel seldom attempt repairs that the company repairman could not have attempted had the required parts been available. Because the Army has several echelons of maintenance, all of which may attempt to repair an equipment, it is not surprising that repair of an equipment may require a considerable period of time -- in some instances, as long as two weeks. Fortunately, however, because of the equipment redundancy used in the Army, such delays may be tolerable, although they certainly are not desirable. In either the Air Force or in shipboard operations, delays such as this would be intolerable.

The preceding paragraphs have shown how the maintenance organization and the tasks performed by the organization have been adapted to the individual tactical situations by the Services. Any direct comparison between these various maintenance groups is difficult because of the differences in the requirements of each organization. Basic to all is the singleness of purpose to meet tactical demands. In the Air Force and the Army, this objective has led to reliance upon special types of equipment redundancy; and, aboard ship, it has meant that a maintenance man must be immediately available for repair when an equipment fails.

2.3.2.7 Effect of Tactical Demands on Personnel Requirements

Tactical demands, again, have dictated requirements for different levels of skill within the particular maintenance groups. During the ARINC Research field investigation, it was observed that the ability and experience of Navy and Air Force technicians was far greater than that of the Army technicians doing line maintenance. The Army technician had received, on the average, eight weeks of formal training; although, in the Signal Repair Teams, the technicians were better trained and more nearly comparable to the Navy technicians. The reference above to the observed difference in

maintenance ability and experience within the three Services should not be construed as a criticism of the Army. It should be remembered that the particular types of electronic equipments under study in the Army were much less complicated than those in the Navy or the Air Force part of the investigation; therefore, they required less maintenance capability. The very short time that the Army has to train soldiers and electronic specialists from the ranks of draftees is indeed a difficult problem; and perhaps a realistic compromise between the desired level of training and the time available for service has been achieved.

When comparisons are made between the engineering maintenance organizations and their corresponding military maintenance groups, the most obvious comparison is that in terms of the number of men involved. This comparison also is one of the most hazardous from which to draw conclusions. While there were fewer engineers than military technicians participating in the test, it must be pointed out the engineers generally had fewer equipments to maintain. The military technicians not only maintained the equipments in their segment of the test, they were also responsible for the repair of other types of equipments. One other circumstance which must be considered when comparing repair times is that the engineers were free from duties other than equipment maintenance, while the military technicians were assigned additional military duties. However, in certain qualified instances, the comparison of manpower is valid in that it does show what a few highly trained engineers can accomplish.

Even in those instances where it can be demonstrated that fewer, better-trained, maintenance personnel (as, for example, the engineers) can replace a greater number of men who are not as well trained, it still may not be valid to conclude that the Services should adopt the first of these alternatives. The Services are more interested in efficiently using the men they presently have. Better training of maintenance men would consume even more of a too-short enlistment period, with the possible consequence of obtaining less efficient maintenance than at present. The Services are presently attempting to improve the quality of maintenance by on-the-job training under the supervision of the more experienced technicians.

In the analysis of the test data, the on-the-job training being received by some of the military technicians had the effect of clouding a comparison of military and engineering manpower in terms of gross numbers of men. The ideal comparison of capabilities would be between the number of supervisory technicians and the number of engineers.

Unfortunately, a comparison of this type cannot be made from the data available. However, in the interest of complete data presentation, the numbers of men in both the engineering and the military maintenance groups are presented, although the reader is cautioned to draw conclusions with care.

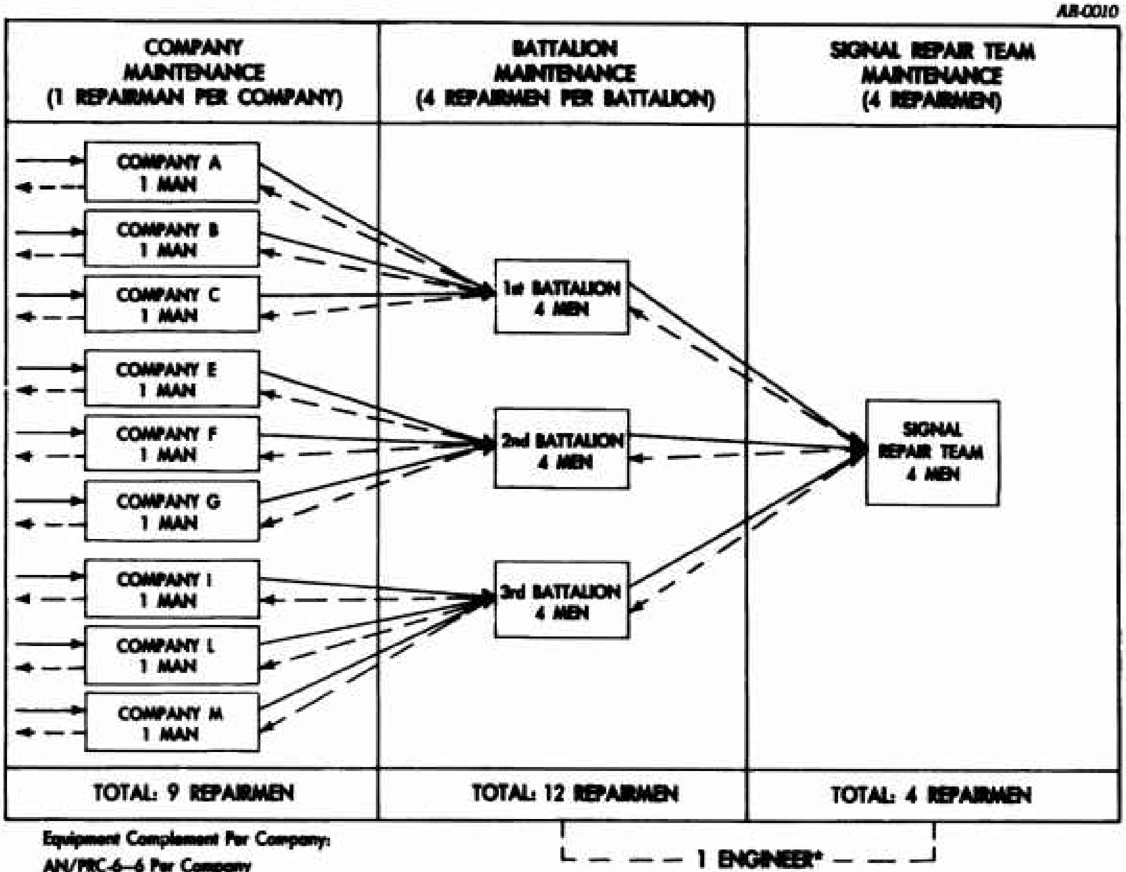
The maintenance of communications equipment in two infantry regiments and two armored battalions was under surveillance in the Army segment of the test. In one infantry regiment, the maintenance was performed by the assigned military technicians, while in the other regiment, one engineer performed the maintenance duties of both the battalion and Signal Repair Team personnel. Figure 1 illustrates the differences in allocation of manpower: A single engineer replaced the 16 men normally required to perform battalion and Signal Repair Team maintenance. The nine repairmen from the individual companies assisted the engineer only to the extent of forwarding failed equipments to him for repair. In the armored battalion portion of the test, one engineer replaced seven military technicians in the battalion and the Signal Repair Team.

In the Air Force segment of the field test, at Carswell and MacDill Air Force Bases, the equipment types under surveillance were: the K System bombing/navigation equipment; the AN/ARC-27 UHF transceiver; and the AN/ARN-14 navigation/radio equipment. Table 2 shows the number of personnel in the military maintenance and engineering groups which were under comparison in the test.

TABLE 2

COMPARISON OF AIR FORCE MILITARY AND ENGINEERING MAINTENANCE GROUPS: CARSWELL AND MACDILL AIR FORCE BASES

Base and Type of Equipment	No. of Military Maintenance Men		Total No. Military Maintenance Men	No. of Engineers
	Flight-Line	Shop		
Carswell Air Force Base				
K-System	3-6	13	16-19	6
AN/ARN-14 and AN/ARC-27	2-3	2	4-5	2
Total No. Maintenance Men	5-9	15	20-24	8
MacDill Air Force Base				
K-System	5	4-6	9-11	6
AN/ARN-14 and AN/ARC-27		6	At Least 6	2
Total No. Maintenance Men	At Least 5	10-12	At Least 15	8



Equipment Complement Per Company:
AN/PRC-6–6 Per Company
AN/PRC-10–6 Per Company

* 1 engineer performed the repair duties of 12 battalion repairmen and 4 Signal Repair Team technicians

FIGURE 1

MAINTENANCE STAFF AND EQUIPMENT FLOW IN TYPICAL INFANTRY REGIMENT

The Navy segment of the test included observation of electronic equipment maintenance organization for both airborne and shipboard equipments. At Norfolk Naval Air Station, two types of airborne equipment were under surveillance -- the AN/ARC-27 receiver-transmitter and the AN/APS-31 and AN/APS-38 anti-submarine and radar-navigation equipment. At this base of operation, there were approximately 40 military technicians -- with varying amounts of technical experience -- who may have been in contact with the equipments undergoing test. The ARINC Research field representatives noted that from four to six of the technicians performed the majority of repairs on the equipments, while the other men, considered to be less skilled, were assigned the more routine maintenance jobs.

For the engineering part of the comparison at Norfolk Naval Air Station, two engineers were assigned to supervise the repair of the two types of equipments in the test. In this part of the study -- as explained in Section 2.3.2.4 -- the engineers did not perform the actual maintenance work, but merely supervised the repairs performed by the Navy technicians.

Aboard ship, all of the equipment maintenance by the military group was performed by 4 technicians, who maintained, in addition to the equipments undergoing test, 43 additional shipboard equipments. One engineer was assigned to maintain the equipments assigned to the engineering segment of the test.

2.3.3 Interaction of the Equipment Operator with the Maintenance Group

The purpose of Sections 2.3.1 and 2.3.2 has been to provide insight into the attitudes of the maintenance groups under surveillance and to describe the structure of the various maintenance organizations. In this section, the effects of the interaction of the operator of the equipment with the maintenance group will be investigated.

2.3.3.1 Judgment of Reliability

Since the operator-maintenance relationship is one which has a definite effect upon equipment reliability, it is appropriate here to state the definition of "reliability" which is used in this investigation:

> "Reliability is the probability that an electronic product will perform satisfactorily for a given period of time under stated conditions of use."

This definition needs little amplification since it has often been discussed in the literature.* In this study, however, the implication in the definition that some observer must judge whether or not the product has performed in a satisfactory manner is of particular interest. In previous studies of reliability conducted in the field, the judge of an electronic equipment's performance has been either the equipment operator or the repairman, or both. For the purpose of this investigation, the reliability data are based upon either the time between operator complaints or upon the time between equipment repairs, or upon both. Thus, within this framework, the ultimate reliability of the equipment is dependent upon how critical the operator and the maintenance man are toward equipment operation. Of these two judges, it can be argued that the operator is the more important, for, although not every operator complaint is followed by a repair, his complaints against the equipment do "trigger off" many of the maintenance actions.

2.3.3.2 Factors Determining Operator's Attitude

Since the reliability of equipments has been used as one of the measures of the effectiveness of each maintenance group discussed in this report, the factors which may determine the operator's attitude deserve some study. If one group of equipment operators is more critical of the equipment than is another, this difference in opinion must be weighted when comparing reliability functions.

The two Air Force bases at which phases of this investigation were conducted provide examples of situations in which the ARINC Research representatives believed the equipment operators had reasons to be especially critical of the equipments. Both of these bases, MacDill and Carswell Air Force Bases, are operated by the Strategic Air Command, whose prevailing philosophy is to keep the flight crews under considerable pressure. The aircraft missions at these bases are

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* ARINC Monograph No. 2: Terms of Interest in the Study of Reliability, C. R. Knight, E. R. Jervis, and G. R. Herd, Aeronautical Radio, Inc., May 25, 1955, Publication No.66.

made to simulate, as nearly as possible, actual wartime conditions; thus the crews are necessarily in a state of nearly continual readiness. Some of the pressures are applied directly to the maintenance organization, while others are in part transferred by the aircraft crews to the maintenance group. At these two bases, a successful mission for the flight crews must include a successful practice bomb run; and, since a successful bomb run is essential to the crew, there may be a natural tendency to want to place the blame for an unsuccessful bomb score upon faulty equipment. Thus, there is good reason for the crews to be critical of the electronic equipment.

When one considers the importance of the K-system bombing/navigation equipment to a successful mission, it is readily understandable that the flight crews may be overly critical of this particular equipment. In support of this belief, the ARINC representatives cited several instances where flight-line maintenance men performed repair actions even when the symptom of malfunction reported by the flight crew could not be verified.

Other evidence also supports this view. The data collected for military maintenance in this test show that, at both Carswell and MacDill, the AN/ARC-27 communications equipment was repaired following each operator complaint; and that repair of the K System followed all but two percent of the instances of operator complaint at Carswell, and all but seven percent of the instances at MacDill. While it would be difficult to demonstrate that some of these repairs were unnecessary, the data concerning the three different engineering maintenance groups responsible for AN/ARC-27 equipment repair show that operator complaints were followed by repair in less than 83 percent of the cases. At Carswell Air Force Base, the engineers made repairs following operator complaint against the K System in almost as many instances (93 percent) as did the military; but, at MacDill Air Force Base, the engineers made repairs on the K System in only 82 percent of the instances of operator complaint. It should be noted that the engineering maintenance groups were believed to be freer from operator pressures than were their military counterparts, although the engineers were still under some pressure, inasmuch as one of the conditions of the test was that engineering maintenance should not interfere with normal military operation.

Under conditions of operational stress -- when the operator of the equipment is under pressure, when the equipment he is using performs an essential function, and when an operator exerts pressure upon maintenance -- the maintenance technician will in turn be under pressure to make repairs.

When conditions such as these occur, if maintenance errs, it will be on the side of safety -- i. e., the repairmen will attempt more repairs than can be justified -- and the net result will be to make equipment reliability appear low, in terms of time between equipment repairs.

Several other instances suggest that operator attitude may have had an influence upon the actions of the maintenance men and upon equipment reliability. Data from the Navy segment of the test indicate that the repair rate of shipboard equipments was highest when the ship was undergoing a shakedown cruise. In this instance, it is reasonable to assume that the operators of the equipment were being especially critical and that equipment malfunctions which might ordinarily have been overlooked were being detected. It is possible that even some needless repairs were made during this cruise. As another example, the ARINC Research representative attached to the Army expressed the opinion that communication equipments used by the company commanders were receiving preferential treatment from maintenance. (These equipments were not included in the test.) It is not clear whether the company commander had demanded better performance or not; however, the effect would have been the same even if the maintenance men had only believed he had done so. In these examples, it is possible that equipment reliability was lowered because the operators were overly critical.

2.3.3.3 Effect of Uncritical Attitude

If the attitude of the operator is uncritical, equipment reliability as measured in the field tends to be higher. Only a few examples of this situation -- most of them observed in the Army segment of the test -- were reported by the ARINC representatives. As an hypothesis, it might be assumed that when the function performed by an equipment is essential to the success of the mission, the operator is more critical of the performance of the equipment; when the function of the equipment is less essential, the operator is less critical. This hypothesis might explain the following example of a situation in which the operator can be considered relatively uncritical of equipment performance. In weighing this example, the reader should bear in mind that, since alternate means of communication usually exist within the Army, operation of a specific communications equipment is not always essential to the success of the mission.

The example referred to concerns the AN/GRC-4 communication equipment, used in the tanks of the armored battalion under surveillance. This equipment consists of two sets, the A set and the B set. Both are essentially the same, except that Set B operates at a higher frequency than does Set A.

Set A is used by the company commander to talk to the tanks in his company; thus, all A sets in the other tanks are left open to the company commander's channel. Set B is used by the individual tanks to communicate with the other tanks in the squad or to talk with the infantry. But, provided there is still some visual contact between the other tanks and the infantry, it is possible to communicate with other tanks or the infantry even if Set B has failed.

In discussions with the ARINC Research representative, the equipment operators expressed the opinion that Set B is unreliable and that Set A is reliable. This opinion apparently stemmed from operator prejudice rather than any conclusion based upon registered operator complaints -- the usual criterion for measurement of equipment reliability. The data showed, in fact, that under engineering maintenance between 80 and 90 percent of all repairs were initiated as a result of the engineer's periodic checks of the equipment; very few repairs were initiated by operator complaints. Even under military maintenance, almost all repairs resulted from periodic maintenance checks, rather than from operator complaints.

The comments of the ARINC Research representative included the opinion that the operators of the AN/GRC-4 equipment were inexperienced to the point of not always knowing whether the equipment was operating or not. This observation was apparently made in relation to both sets, but particularly in relation to Set B. It was reported that the operators appeared to be unaware of some of the functions which could be performed by the equipment.

The combination of circumstances described above produced a situation in which (1) the equipment operators considered the equipment unreliable and thus, superficially at least, appeared to be highly critical in their attitude toward the equipment; (2) because of their inexperience and lack of familiarity with the equipment, the operators actually were relatively uncritical -- as evidenced by the infrequency of reported complaints requiring repair work; and (3) the small number of complaints registered by the operators produced a false impression of good equipment reliability.

An additional factor to be considered is that the receiver of Set A has built-in meters which make identification and diagnosis of malfunctions somewhat easier than for Set B, which does not have such meters. It is almost certain that, for this reason, the A sets were better maintained.

2.3.3.4 Effect of Operator's Opinion of Maintenance

Another type of motivation for operator attitude is found in the operator whose judgment of equipment performance is conditioned by what he believes the maintenance man can accomplish. For example, ARINC Research representatives observing the AN/PRC-6 communication equipment in use by the infantry noticed a reluctance on the part of the operators to report marginally operating equipment to the repairmen. The argument given by several of the operators was that there was a good chance the equipment would not be repaired by maintenance; also, if the equipment were turned in for repair, it might be as long as two weeks before the equipment would be returned.

A situation of this type is particularly difficult to appraise. The reliability function based upon field data would show the equipment to be reliable, even though the operating personnel did not consider it reliable and deliberately refrained from turning it in for repair.

On behalf of the maintenance men in this instance, a word of explanation is warranted. The AN/PRC-6 communication equipment suffered many failures immediately following a repair which could be traced to weak or dead batteries. These batteries deteriorated rapidly, even in shelf-life. Another common problem which in some instances led to erratic equipment operation and initial failures following a repair -- and even contributed to the delay time in repair -- was essentially a human-engineering problem. The tube shields on the subminiature tubes in the AN/PRC-6 equipment are held in place by a clamp secured by a very small set-screw; moreover, the portion of the equipment where these tubes are located is almost inaccessible to maintenance. The "clamping-in" of the tube is essential to insure adequate contact between the tube pins and the socket, but, since the tube is nearly inaccessible, it is not always properly seated and is sometimes the cause of initial failures or erratic operation. Often the tube-shield set-screws were lost in the field, and delays in repair would occur while replacements were awaited. Figure 2 shows the reliability functions for AN/PRC-6 equipments maintained by both engineering and military maintenance, calculated on the basis of equipment operating time between repairs. The figure illustrates the concept of an equipment reliability function which does not start at one at zero operating time -- specifically, it shows more than 20 percent <u>initial failures</u>. A large proportion of these initial failures were due to the battery problem.

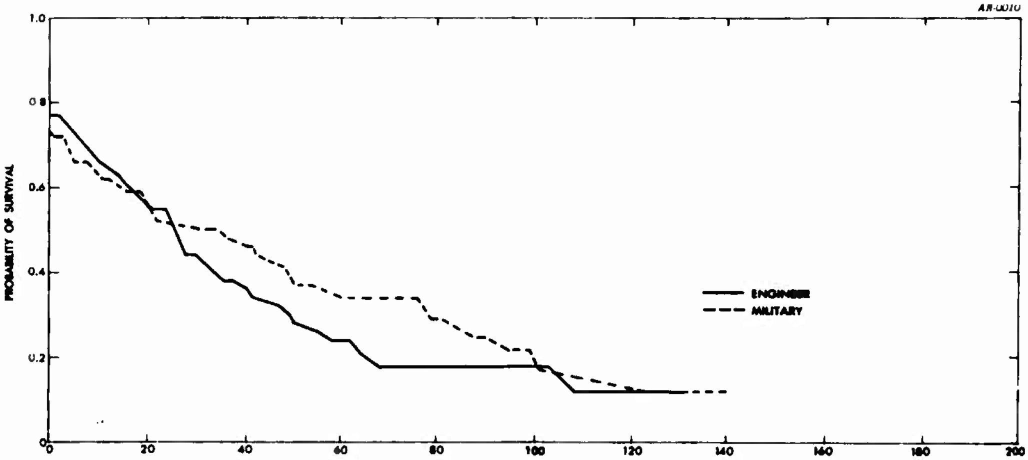


FIGURE 2

ENGINEERING VS. MILITARY MAINTENANCE: OBSERVED RELIABILITY FUNCTIONS FOR AN/PRC-6 EQUIPMENTS IN EUCOM

While no other examples are cited directly to demonstrate a dependence of operator attitude upon maintenance effectiveness, the same possibility exists for several other equipment types studied during this test. For example, one observation which has been somewhat difficult to explain is that, from periodic checks on equipments by ARINC Research representatives, it was determined that the engineers maintained their equipments at a higher performance level than did the military. Yet, the reliability functions for the engineers' equipments, based on time between operator complaints, do not necessarily indicate that the higher performance levels are reflected in higher reliability. However, two tentative hypotheses are offered: (1) if performance is maintained at a lower level, the operator is less critical, and (2) the operator is not particularly sensitive to performance levels above a certain minimum or threshold value. If he can communicate, he is not too concerned with the quality of the communication.

2.3.3.5 <u>Operator's Attitude vs. Equipment Function</u>

Analysis of AN/ARC-27 equipment data from several bases suggests, at least as a hypothesis, that the operator's opinion of equipment performance is related to the function

the operator is attempting to perform with the equipment -- i. e., if his dependence upon the equipment changes with time, his degree of criticalness also changes. This situation is probably more relevant to aircraft equipment, where the mission and the equipment usage are well defined in time, than to other types of equipment. While it is not certain the following example actually demonstrates a valid hypothesis concerning the effect of operator attitude upon equipment reliability, the example itself is important because it demonstrates strong effects of conditions at the particular base.

Data collected in a recent ARINC Research Corporation investigation at Cabaniss Naval Air Station (a base not included in this particular study) are presented in Table 3 to illustrate the hypothesis outlined above. The table shows the distribution, by time intervals, of operator complaints registered against the AN/ARC-27 equipments.

TABLE 3

DISTRIBUTION OF OPERATOR COMPLAINTS BY INTERVALS OF TIME: AN/ARC-27 EQUIPMENTS AT CABANISS NAVAL AIR STATION

Time of Complaint	Percentage of Complaints
On the ground, just prior to take-off	23%
First 5 minutes of flight	27
From 5 minutes of flight to mid-point of mission*	41
Last half of mission	9
Total	100%

* Average mission length is 2.5 hours; mid-point of mission was assumed to be 1.25 hours.

Table 3 indicates that one-half of the operator complaints were registered either on the ground prior to take-off or during the first five minutes of flight; only nine percent of the failures were reported in the last hour and one-quarter of flight. It is assumed a similar tabulation of operator complaints for Norfolk, Carswell, and MacDill --

the three bases in this test which used AN/ARC-27 equipments -- would exhibit the same high initial probability of operator complaint during a mission. One of the important points established by this table is that it contradicts the most common assumption made regarding equipment reliability — i. e., that the probability of equipment failure remains constant in terms of operating time. Table 3 indicates that the probability of complaint is not nearly as great during the last half of the mission as during the first few minutes of the mission.

Several reasons have been advanced as to the probable cause of the higher percentage of operator complaints early in a mission. Some of these are:

(a) The equipments are affected by some physical phenomenon, such as the electrical shock to tubes when power is first applied or the physical shock associated with take-off. (Both of these possible causes have been examined and have been rejected on the basis of engineering analysis of the AN/ARC-27 equipment.)

(b) The performance requirements of the equipment are more demanding on the ground than in the air. A possibility exists that because of obstructions on the ground, communication with the control tower before take-off may be more difficult than communication with other aircraft in the air later in the mission.

(c) Calibration, adjustment, and alignment of the equipment may be more difficult when the equipment is first turned on, and may become easier after the equipment has had a chance to warm up.

(d) The operator may be more critical of equipment performance while on the ground. It can be argued that it is far better to abort a mission on the ground or early in the mission rather than later in the mission.

(e) Prior maintenance of the equipment may have failed to correct an equipment malfunction or may even have introduced a new one. Such a malfunction would be detected by the operator early in the mission.

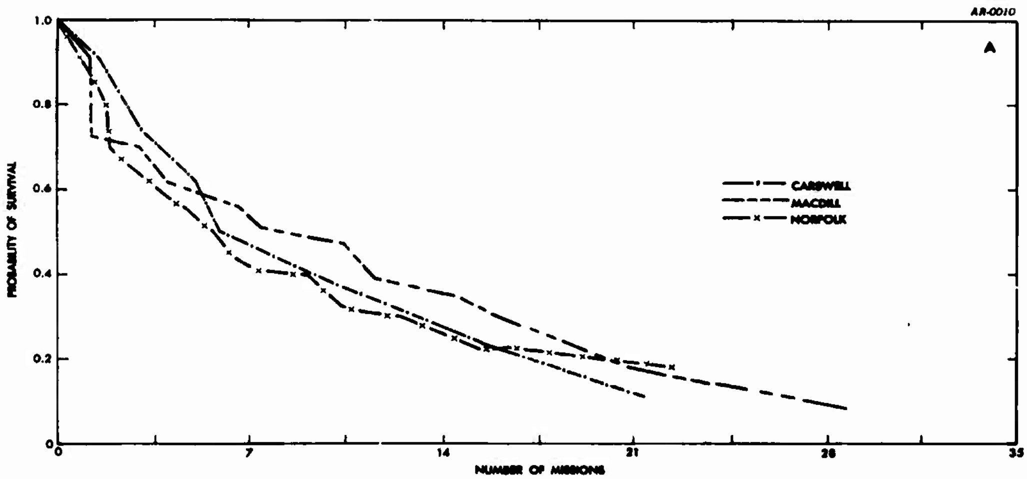
(f) The operator may demand a higher level of performance of the equipment early in the mission. For example, the operator is more critical of the performance of a bombing/navigation system up to the time of the bomb run (first half of the mission) than he is from this point in time to the end of the mission.

(g) Any failure of an operator to correctly energize or operate equipment is most likely to show up before take-off or -- in the case of equipment not normally checked before take-off -- during the first portion of the flight mission.

Which one of these causes, or which combination of causes may dominate the Cabaniss data is not known, but it does seem a fair hypothesis that early in the mission either the operator has good reason to be more critical or, for no particular reason, is more critical. After the mission is a few minutes old, the operator becomes less critical of the equipment. Since most operator complaints occur during the first few minutes of flight, the additional time flown in the mission contributes very little, in terms of percentage, to total operator complaints. Thus, whether a mission is long or short, there is little difference in the total number of operator complaints, although the length of the mission does make a considerable difference in the reliability function based upon hours between operator complaints.

Figure 3, part A, shows a comparison of reliability functions for AN/ARC-27 equipments maintained by military technicians at Norfolk, Carswell, and MacDill, calculated on the basis of number of missions flown between operator complaints. The functions are reasonably similar, and appear to demonstrate quite clearly the above-mentioned phenomenon that the probability of operator criticism of an equipment is greatest early in a mission. If, on the other hand, the comparison is made in terms of the number of operating hours between pilot complaints, as illustrated in part B of Figure 3, the three reliability functions differ materially. Figure 3 thus indicates that the probability of operator complaint per mission is apparently about the same at all three bases; further, that operator complaints are related to the mission and -- judging by the data from Cabaniss Naval Air Station presented in Table 3 -- to the early part of the mission. The foregoing analysis also suggests that the length of the mission contributes very little to the number of operator complaints.

The preceding example of operator complaints registered against the AN/ARC-27 equipments maintained by military technicians is not an isolated case. The AN/ARC-27 equipments maintained by the engineers exhibited the same trends; and, when a comparison of K-System reliability at Carswell and MacDill Air Force Bases is made, the data again show the same trends for both engineering and military maintenance of the equipments.



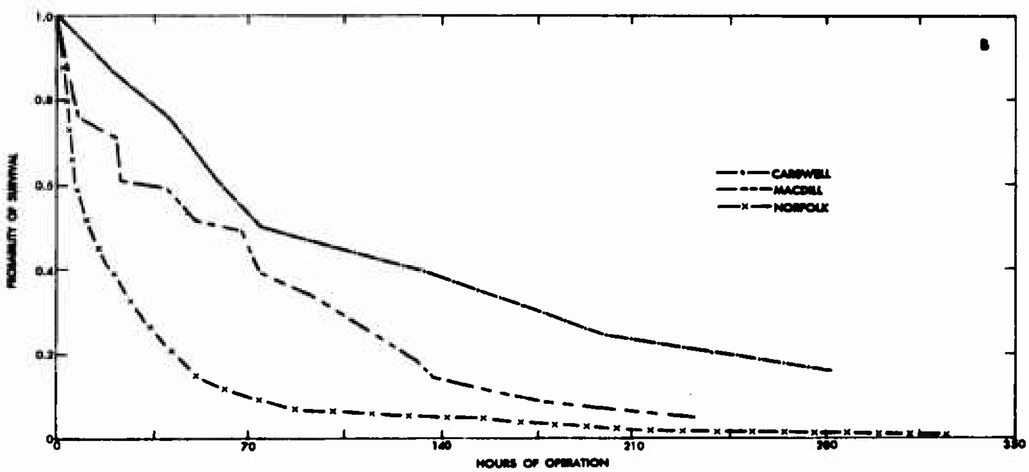


FIGURE 3

COMPARISON OF EQUIPMENT RELIABILITY FUNCTIONS FOR THREE MAINTENANCE GROUPS BASED ON (A) MISSIONS FLOWN BETWEEN PILOT COMPLAINTS, AND (B) HOURS OF OPERATION BETWEEN PILOT COMPLAINTS: AN/ARC-27 EQUIPMENTS UNDER MILITARY MAINTENANCE

The foregoing analysis based on AN/ARC-27 data illustrates one of the hazards encountered when comparisons of maintenance groups are made in terms of the equipment reliability achieved. Any comparison across bases must be considered cautiously. Only at the same base where operational conditions are similar can direct comparisons safely be made. The similarity of equipment reliability achieved by engineering groups at different bases is far less than is the similarity of equipment reliability achieved by engineering and military maintenance groups at the same base.

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3. MAINTENANCE AND RELIABILITY

The two preceding sections of this report have outlined the scope of the investigation and the nature of the problems encountered. In this section, the data collected during the field-observation phase of the investigation will be analyzed, and explanations of the interactions of the factors under observation will be advanced.

Specifically, Section 3.1 is an analysis of the actions taken by maintenance personnel during equipment repair; Section 3.2 analyzes the effects of maintenance actions upon electron tube reliability; and Section 3.3 examines the effects of electron tube reliability on equipment reliability.

Although the ARINC Research Corporation test must be considered large in terms of total quantities of data obtained, when a particular type of part in a specific type of equipment at one base is examined, the quantity of failure data available for study is often extremely small. Accordingly, detailed analyses are made only where warranted by the amount of data. Certain illustrative examples which are well supported quantitatively have been included, although they are not a result of this field test, but have been drawn from previous ARINC Research experience. Thus, the data do not represent all equipments or all bases equally well. However, those data which are presented are considered to be typical and the conclusions drawn from them are believed to be valid.

Where the equipment types are similar, it might be suggested that some types of data from the different bases be pooled. However, a strong argument against pooling is that the various maintenance groups are distinctly different, and this difference would be reflected in the data. The usual argument for pooling -- that one gains greater accuracy -- is lost because of the heterogeneous nature of the samples which would be pooled. In fact, it is this very heterogeneity that we wish to examine.

The analyses in this section are based primarily upon data relating to the AN/ARC-27 airborne communications equipment; however, where applicable, data from other equipments are included.

3.1 Actions Taken by the Maintenance Technicians at Repair

This section presents three different analyses of the "maintenance actions" taken during equipment repair. The most obvious measure of repair -- i. e., the time required to make a repair -- will be examined in Section 3.1.1. In Section 3.1.2, the analysis concerns the frequency with which maintenance technicians attempted various repair actions -- for example, adjustments, tube replacements, and other types of part replacements; and, in Section 3.1.3, the distribution of the numbers of tubes removed at repair will be examined.

Some of the factors believed to have an effect on these maintenance actions will be discussed at the beginning of each analysis, as a basis for the presentation of hypotheses by which the data can be interpreted.

3.1.1 The Time Required to Repair an Equipment

One of the first questions generally asked in a maintenance study is: "How long does it take to repair an equipment?" To this should be added the question: "What are some of the causes which contribute to this time?"

It should be quite simple to describe what the maintenance man is doing to repair an equipment and how long it takes him to do it -- for example: X minutes to determine that the equipment needs to be repaired; Y minutes to diagnose the cause of the malfunction; and Z minutes to repair or to replace the unit causing the malfunction. Even if the first repair diagnosis were wrong and a second one had to be made, the times involved could be classified and measured. Data based on reasoning of this type, although extremely useful, furnish very few of the reasons why the repair times are as long as they are. The "why" involves the skill and experience of the maintenance man, the simplicity of diagnosis and repair of the equipment, and many other things which are more difficult to evaluate and to relate to time. The basic difficulty in the present analysis, however, is that the data on repair times collected in this investigation show only the active time spent in maintenance of an equipment; because of the additional complexity that would have been added to the test, this time is not broken down into the several steps of repair. Although some examples are presented which appear to substantiate the hypotheses advanced, the discussion of time which follows is based more upon assumed causes than upon verified causes.

3.1.1.1 Diagnosis of Cause of Malfunction

When equipment failure can always be traced to just one cause and the maintenance man, through experience, knows the cause of malfunction, repair time is essentially the time required either to repair the cause of malfunction or to replace the malfunctioning unit with a new one. Repair times for this simple type of equipment malfunction would be nearly uniform -- the only variance would be that which might be caused by the differences in manual dexterity of the maintenance men.

However, when there are many possible causes for an equipment failure, with no single cause being predominant (a situation true even of the smallest electronic equipments), it is not reasonable to expect all repair times to be approximately the same. For complex electronic equipment, considerably more time must be expended in the diagnosis of the cause of malfunction, and proportionately less time in the physical repair of the malfunction.

It seems logical to believe that in diagnosing causes of failure of the more complex types of equipment, maintenance men generally proceed by a process of elimination. From observation of the nature of the malfunction, the maintenance man probably will think of several possible causes of failure. The several possibilities will be based in part upon his past experience with the equipment and in part upon the thoroughness with which he has observed the symptoms of malfunction (this thoroughness may depend upon the availability of test equipment).

The repairmen's first theories concerning causes of failure probably will be of a general nature -- e. g., "it is a mechanical type of failure," or "it is an electrical type of failure"; also, it is probable the cause will be associated with the larger units of the equipment -- "the trouble is in the computer," or "the trouble is in the radar." After he has eliminated some of these general diagnoses of equipment failure from consideration, the maintenance man will select the more likely causes for detailed analysis. It is quite possible that up to this point, he has done nothing physically; he has reached this level in the problem by observation and by "thinking it through". However, the time consumed by this diagnosis should rightfully be considered part of the repair time.

Following the preliminary diagnosis, the maintenance man may be required to make measurements at test points as a means of isolating the source of malfunction to a particular circuit, and, finally, to an individual part within the circuit. At the part level, unless the cause of malfunction is immediately obvious, the maintenance man will have to resort to part substitution to finally eliminate the cause of equipment failure. It is possible that even after this effort, the malfunction will not have been corrected. In this event, the maintenance man must retrace his steps and pursue another possible alternative. This is where "luck" plays an important role in the repair process -- the luck of having selected the correct cause of failure from the several possibilities considered, and of even having considered the right cause of failure from the original set of possible causes.

All repairs of course do not proceed in such an orderly manner. At times, several steps in the process may be eliminated. As an example, during this test ARINC Research field representatives observed military maintenance men, when pressed for time, initiate the repair action by tube substitution.

Some refinements of this basic method of repair by the process of elimination have been designed and are being taught to maintenance personnel. For example, the elimination process can proceed by: (1) testing the inputs and outputs of the suspected black boxes of the system, or (2) by tracing the signal through a complete function. The effectiveness of the second method is enhanced if the entire function is contained within one unit; thus, the choice of one method over the other may be completely dependent upon the design of the equipment. Sometimes, the elimination process is systematized to the extent that the equipment is always checked in a certain sequence.

It is believed that most diagnoses of malfunctions are based, essentially, on the process of elimination. To make a diagnosis and to complete the repair is analogous to following a path which has many forks, one of which eventually leads to the cause of malfunction. The problem is to select the right fork or at least to spend a minimum of time on the wrong fork. Each fork in the path represents a decision which has to be made -- i. e., which major unit contains the malfunction, which assembly within the major unit, which subassembly within the assembly, which circuit within the subassembly, and which part within the circuit. Down to the part level, logic, experience, test equipment, and test points are of prime importance. At the part level, unless the defective part is visually obvious, repair probably will

proceed by part substitution, because at this level it is difficult to make further circuit analyses. If at any time a dead end is reached because a bad decision has been made somewhere along the path, the repair man must retrace his steps and try a new path.

The implication in this approach to equipment repair is that if the equipment has not been repaired at a particular time, t, the remainder of the time required to complete the repair is essentially independent of t, the prior time spent in repair. The future time expended is assumed to be a function of the number of decisions which will have to be made and the correctness with which they will be made. With even a moderately complex equipment, the maintenance man cannot always be certain he is following the right path. At any time in the process he may reach a dead end and have to start over. Because of this uncertainty in many repairs, the total time spent in repair is essentially unpredictable in any but a statistical sense.

3.1.1.2 Theoretical and Observed Maintainability Functions

The reasoning set forth above leads to a particular type of theoretical maintainability function.* Stated formally, if an equipment repair is not completed at time, t, it is assumed the probability of completing the repair in (t + h) hours is independent of t. It follows from this assumption that the total repair times will be exponentially distributed and the maintainability function -- i. e., the probability of completing the repair in T or less hours -- will be of the form

$$M(T) = 1 - e^{-T/m} \quad , \tag{1}$$

where m is the average time required to make a repair.

In the following paragraphs, repair-time data for the AN/ARC-27 equipment at Cabaniss Naval Air Station (a base of operation not included in this particular investigation) will be employed to evaluate the maintainability function derived in equation (1). The Cabaniss data were chosen for this purpose because they represent a large quantity of repair-time observations; also, they permit the separation of repair times into groups that correspond to the number of tubes removed at each repair. While the number of tubes removed at each repair does not necessarily correspond exactly to the

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* In this report, the term "maintainability function" refers to the probability that an equipment can be repaired within a specified time.

total number of decisions made at each repair, these numbers should be related -- i. e., the more tubes removed, the more decisions; and the more decisions, the longer the repair time.

Table 4 shows the number of tubes replaced per repair and the average time required to make the repairs of AN/ARC-27 equipments at Cabaniss Naval Air Station.

Table 4 indicates that as the number of tubes replaced per repair increases, the average repair time also increases. However, in the range from two tube replacements to nine tube replacements per repair, the average repair time remains reasonably constant -- i. e., at about 2.5 hours. The most noticeable changes in average repair time occur between no tube replacements and one tube replacement, between one tube replacement and the range from two and nine replacements, and between the two-to-nine range and ten or more replacements.

TABLE 4

NUMBER OF TUBE REPLACEMENTS AND AVERAGE REPAIR TIMES: AN/ARC-27 EQUIPMENTS AT CABANISS NAVAL AIR STATION

No. of Tubes Replaced per Repair	Total No. of Repairs	Percentage of Total Repairs	Average Time to Repair (in hours)
0	172	53.6%	1.00
1	58	18.1	1.46
2	35	10.9	2.57
3	16	5.0	2.92
4	12	3.7	2.68
5	8	2.5	2.44
6	7	2.2	2.71
7	4	1.2	2.08
8	2	0.6	2.50
9	1	0.3	3.00
10 - up	6	1.9	4.30
Average No. Tubes 1.4	321	100.0%	Average Time 1.62

Those instances where only one tube was replaced probably represent the majority of situations in which the defective tube was almost immediately obvious; while those instances where from two to nine tubes were replaced probably correspond to the more difficult type of repair, in which several tubes, not immediately obvious as defects, were replaced before the equipment malfunction was corrected. The varying number of tubes could be due to trial-and-error replacement of tubes when the repair reaches the circuit level. The instances of ten or more tube replacements are suggestive of the type of repair in which several alternative paths were followed completely before the repair was accomplished. Each of these alternatives could have resulted in the replacement of several tubes. While this analysis of Table 4 is only speculative, it does suggest the manner in which tube removals could be related to repair time.

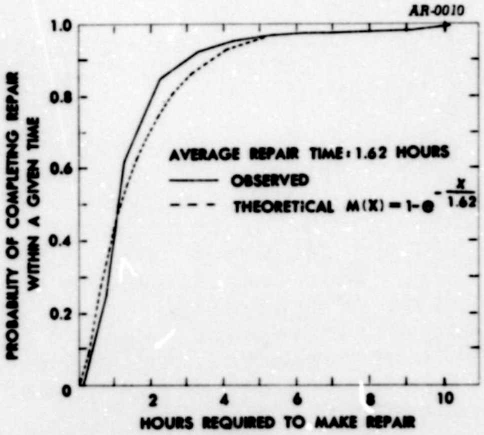

FIGURE 4

OBSERVED AND THEORETICAL MAINTAINABILITY FUNCTIONS: AN/ARC-27 EQUIPMENT AT CABANISS NAVAL AIR STATION

In Figure 4, the same repair-time data from Cabaniss Naval Air Station are plotted as a maintainability function and are compared with the theoretical maintainability function. The estimate of average repair time obtained from the sample was used for the m value in the theoretical equation in Figure 4. The theoretical maintainability function fits the observed data reasonably well, although it does not offer a particularly good explanation of some of the longer repair times.

Figures 5, 6, 7, and 8 illustrate samplings of maintainability functions plotted from observed repair-time data collected during the ARINC Research field investigation. In each of these figures, military maintenance repair times are compared with the engineering maintenance repair times for the same equipment types. It should be noted that the curves are reasonably comparable to the type of function suggested by the theoretical model developed in Equation (1). Thus, on the basis of the information contained in these illustrations, one might conclude that a considerable part of the repair time is consumed by diagnosis and decision-making; that for many malfunctions the proper repair action is not obvious, but must be sought out; and that the repairman runs the

chance of making some wrong decisions before he makes the correct decision which will ultimately lead to the repair of the equipment.

Figure 5 presents maintainability functions for the TED-3, a UHF transmitting equipment used aboard ship. This equipment is comparatively simple to maintain. The predominant sources of trouble are wear-out of the blower-motor brush and failure of the 4X150 transmitting tube, in that order. Those repairs which included replacement of tubes -- whether of type 4X150 or of other types -- took somewhat longer than repairs in which tubes were not replaced. When tubes were removed, the average time required for repair was 6.7 hours for the Navy technicians and 5.5 hours for the engineers.

The predominance of two sources of malfunction, brush wear-out and tube failure, is not particularly well illustrated in the maintainability functions; but it is more evident in the frequency distributions of repair time. These distributions, for both military and engineering maintenance, are also shown in Figure 5. The earliest peak in the frequency-distribution graphs corresponds primarily with the time required to replace the brushes, and the second peak and the longer repair times correspond primarily with repairs which included tube removal.

Maintainability functions for AN/ARC-27 UHF transceivers used in aircraft at Norfolk Naval Air Station are shown in Figure 6. This equipment is more complex than the TED-3. While the maintainability functions are similar in shape to those in Figure 4 for the AN/ARC-27 equipments at Cabaniss, they show that the average repair performed by both the engineers and the Navy technicians took longer at Norfolk than did the average repair performed by the Navy technicians at Cabaniss. The cause of this difference in repair time is unknown; however, it is believed to be associated in some manner with the difference in environment at the two bases. At Norfolk, the average time required by the engineers to repair the AN/ARC-27 was less than that required by Navy technicians, although in approximately 90 percent of the repairs there was no appreciable difference in repair time. The difference in average time to repair is due to a few extremely long repair times which occurred during military maintenance but not during engineers' maintenance. This difference is illustrated by the frequency distributions of repair times in Figure 6.

Figure 7 presents comparative maintainability functions for the K-System bombing/navigation equipment used in B-36 aircraft at Carswell Air Force Base. From the point of view

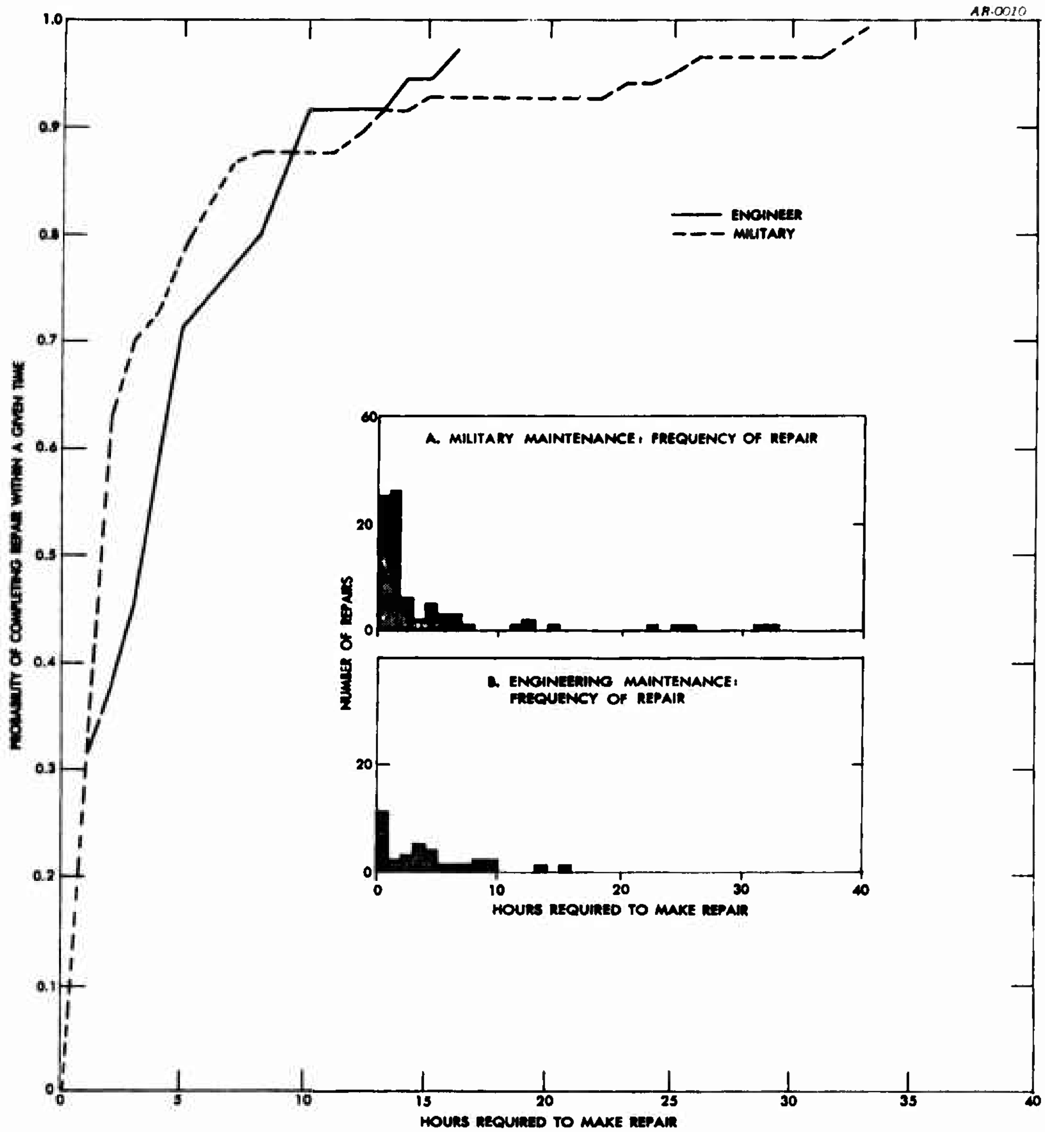

FIGURE 5

ENGINEERING VS. MILITARY MAINTENANCE: OBSERVED MAINTAINABILITY FUNCTIONS FOR TED-3 SHIPBOARD EQUIPMENT AT NORFOLK NAVAL STATION

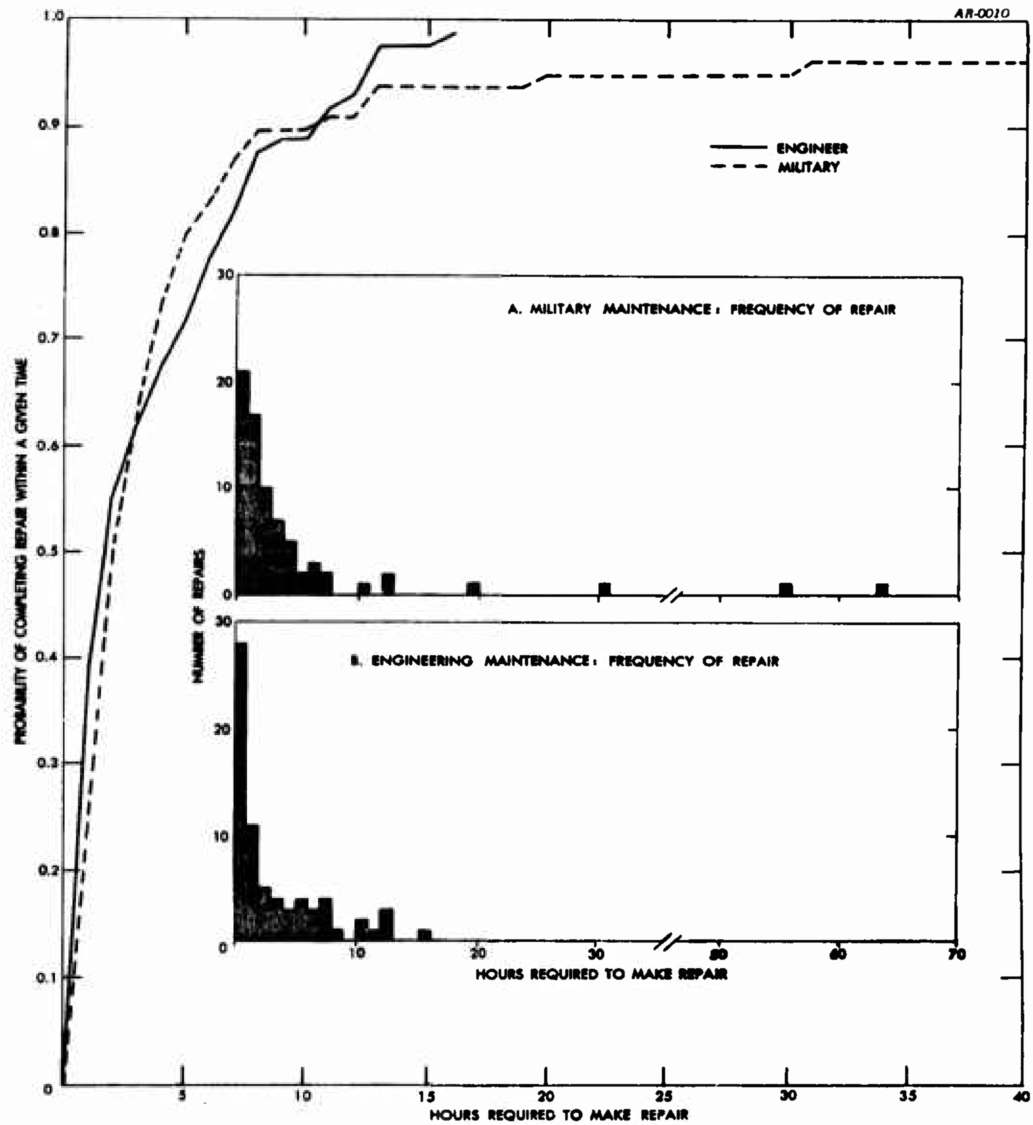

FIGURE 6

ENGINEERING VS. MILITARY MAINTENANCE: OBSERVED MAINTAINABILITY FUNCTIONS FOR AN/ARC-27 EQUIPMENTS AT NORFOLK NAVAL AIR STATION

of maintenance, the K System is the most complex equipment that was studied in this test; malfunctions may originate in a multitude of possible sources. This equipment required the longest time to repair; however, attention is called to the fact that in Figure 7, the repair times include both time spent on flight-line repair and repair time in the shop. As was true generally for all equipment types in the test, the engineers, on the average, spent less time on an individual repair than did the military technicians. The repair-time frequency distribution for the K System shows that it was virtually impossible to repair the system in less than two hours. This apparently is a consequence of the difficulty in diagnosing causes of malfunction. Even when the maintenance men decided that no trouble existed in the system (after examination which was the consequence of an operator complaint), the elapsed time to arrive at this conclusion was 10 hours for the military technicians and 4.1 hours for the engineers.

Another feature of interest in the distribution of K-System repair time for military maintenance is the high frequency of repair-time intervals which are multiples of four and eight. This suggests a tendency by the military technicians to make the repair last until the end of the shift, and it also indicates that the work load was sufficiently light that they could spend the entire day on a single repair. It should be noted that the repair times for the engineers do not suggest similar circumstances. However, this is as would be expected -- assuming that the above hypothesis concerning military maintenance is correct -- because the engineers had nothing to gain by extending a repair.

The maintainability function illustrated in Figure 8 is for the AN/PRC-6 Handy Talkie, used by the Infantry. This again is a fairly simple equipment from the point of view of maintenance; however, no one cause for malfunction seemed to predominate in the data. The repair time shown for the military technicians represents only that time spent in active maintenance by the men in the Signal Repair Teams, and it does not include any repair time accumulated at the company or battalion level.

While the theoretical model expressed in Equation 1 fits each of the observed maintainability functions reasonably well, there are several reasons why this simplified model does not completely describe repair-time data. Some of the factors that should be considered in a more sophisticated model are:

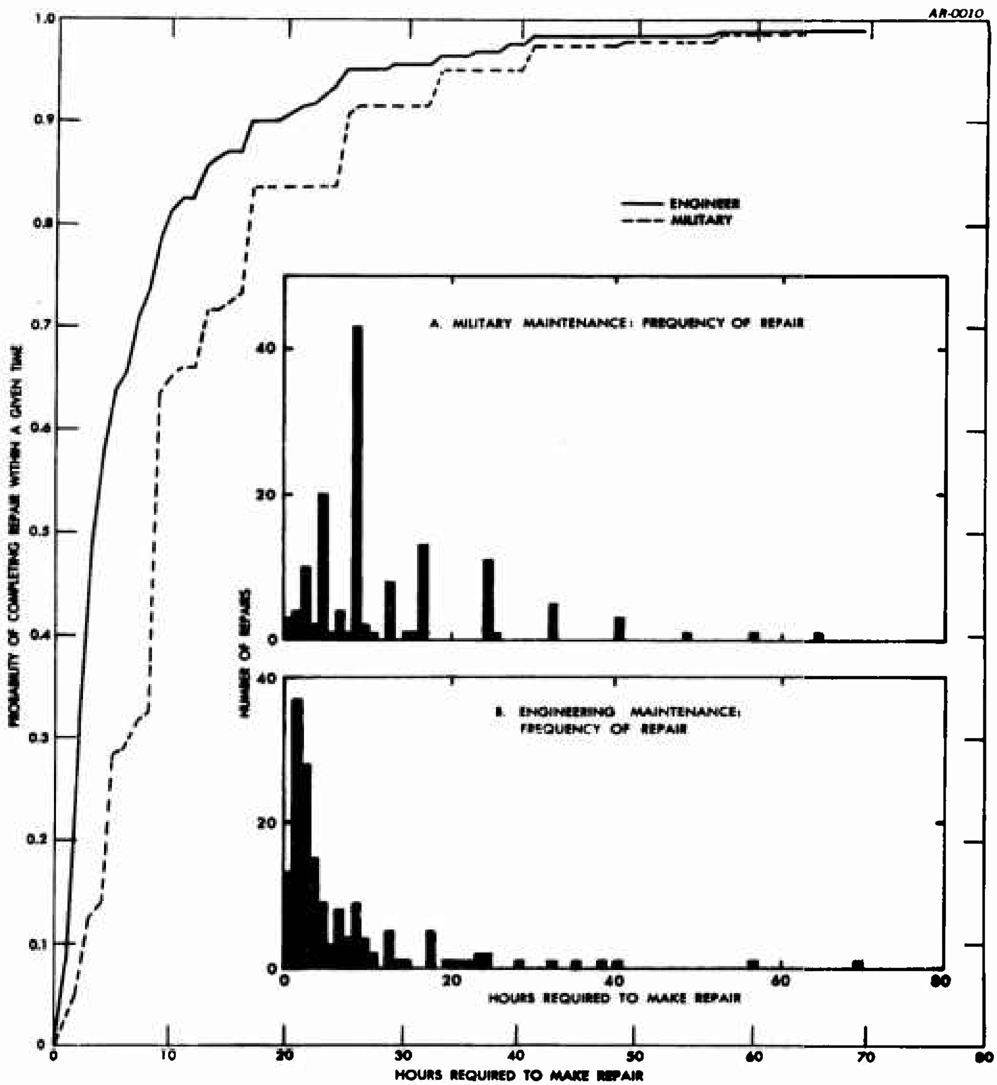

FIGURE 7

ENGINEERING VS. MILITARY MAINTENANCE: OBSERVED MAINTAINABILITY FUNCTIONS FOR K SYSTEMS AT CARSWELL AIR FORCE BASE

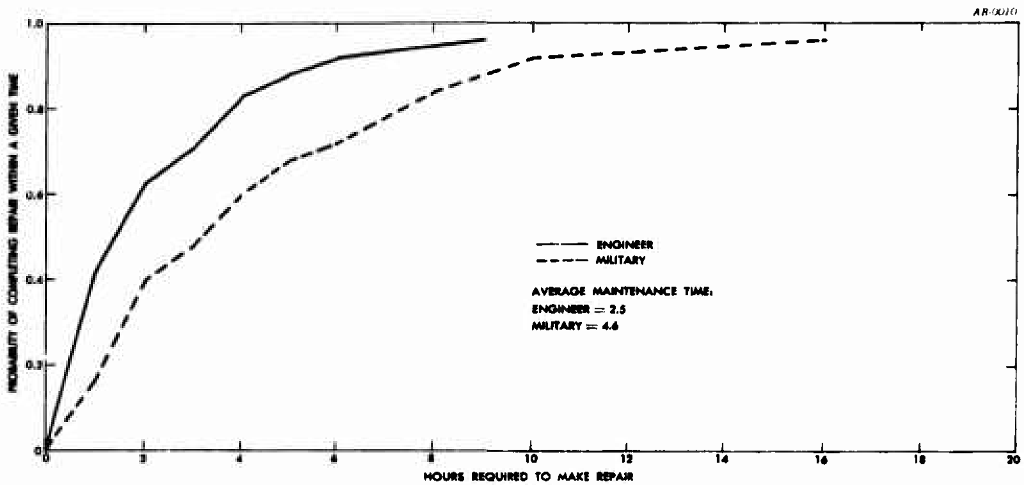

FIGURE 8
ENGINEERING VS. MILITARY MAINTENANCE: OBSERVED MAINTAINABILITY FUNCTIONS FOR AN/PRC-6 EQUIPMENTS IN EUCOM

(a) The effect that may be produced on the data when several maintenance technicians work on a single repair -- for example, when both flight-line and shop-maintenance personnel work on the same equipment or when several maintenance men work simultaneously as a team on the same repair.

(b) The ease or difficulty experienced in the diagnosis of certain types of malfunctions, and whether or not there is a preponderance of a certain type of malfunction -- which would invalidate the assumption made in the model.

(c) Variations in the shop workload, which may change the average time required to make a repair. When the workload is heavy, it is reasonable to expect the maintenance men to work faster than when the workload is light.

(d) The differences in degree to which a repair is attempted. Is the repair considered as being complete when a major subunit that contains the malfunction has been isolated and has been replaced, or is the repair considered as being complete when the malfunctioning parts within the major subunit have been replaced?

(e) The possibility that maintenance men may have introduced a new malfunction in making the repair.

3.1.1.3 Average Repair Time

Since the configurations of the observed maintainability functions are reasonably well described by the theoretical model, little additional information is gained by a more detailed consideration of the distribution of individual repair times. For all practical purposes, it is just as informative to use the simpler procedure of examining repair times in terms of the average time spent on individual equipment repairs. Table 5 summarizes the data on average repair time for all equipment types under surveillance in the field test.

The repair time, as referred to in Table 5, represents those maintenance actions in which:

(a) the technician or engineer was aware of some symptom of equipment malfunction, although not necessarily of the same symptom reported by the operator, and

(b) some action was taken which may have ranged from the simplest action of turning on a switch if the operator had failed to do so, to the more complicated replacement of component parts or whole units of the equipment.

Not all repairs were completed; in a few instances, when the technician was unable to make the repair by isolating the failed parts, repair consisted of substitution of spare major assemblies for the failed assemblies. The failed assemblies were then sent to the depot for final repair. The degree of completion of a repair was dependent upon the objectives of the different maintenance groups. Some attempted to isolate the source of failure to a replaceable part, while others attempted only to isolate the failure to a larger replaceable unit.

It is evident from Table 5 that the engineers generally took less time to repair the equipment than did the military technicians at the same base. In only 4 of 13 instances did the engineers require more time than the technicians. The most notable exceptions were those involving the AN/URR-13B shipboard equipment and the AN/ARN-14 aircraft equipment at MacDill Air Force Base. Both of these equipments are reasonably simple to repair and both are quite reliable. However, the engineer who performed the maintenance on the AN/URR-13B equipment reported that he devoted a considerable amount of time to tracing the source of failure to the correct part in order to eliminate unnecessary part replacement, and that he also expended a considerable portion of the repair time in

TABLE 5

SUMMARY OF REPAIR TIME

Equipment Type	Base*	Average Time in Hours Required to Repair Equipment	
		Military	Engineering
AN/ARC-27	CAFB MAFB NNAS	7.1 4.5 4.6	2.4 5.3 3.2
K-System	CAFB MAFB	11.6 5.4	6.3 3.7
AN/ARN-14	CAFB MAFB	9.5 1.3	2.7 4.7
AN/APS-31 AN/APS-38A	NNAS	4.0	2.5
AN/URR-13B	NS	0.9	4.5
TED-3	NS	3.7	3.8
AN/PRC-6	I	4.6	2.5
AN/PRC-10	I	4.7	3.4
AN/GRC-4	A	2.6	1.1

* Abbreviations for bases in test: Carswell Air Force Base, CAFB; MacDill Air Force Base, MAFB; Norfolk Naval Air Station, NNAS; Norfolk Naval Station (Ships), NS; Infantry, Europe, I; Armored, Europe, A.

testing the equipment after parts were replaced. On the other hand, the ARINC Research observers reported that the Navy technicians -- who were somewhat short-handed -- attempted to make the repairs as quickly as possible. This same observation may possibly explain the differences in repair time for the AN/ARN-14 equipment at MacDill Air Force Base.

In Table 5, the repair times for similar types of equipment in use at different bases show nearly as much variation for the engineers as for the military technicians. This variation in time is suggestive of strong base influence -- arising, for example, from different philosophies of repair and differences in work loads. Average repair time apparently is not uniquely determined by the type of equipment to be repaired, nor will qualification of the repair time by the skill of the maintenance men explain the repair time differences.

In Figure 9, the average repair time required for engineering and military maintenance of the AN/ARN-14, AN/ARC-27, and K System at Carswell and MacDill Air Force Bases is shown in relation to equipment complexity as measured by the number of tube sockets. A slight correlation is apparent; however, more than just the number of tubes used in the equipment must be considered to explain the length of repair times.

Figure 9 demonstrates an appreciable difference between repair times for military maintenance at Carswell and the other three maintenance groups. This difference may be attributable primarily to the difference in approach to repair by the military technicians at Carswell Air Force Base.

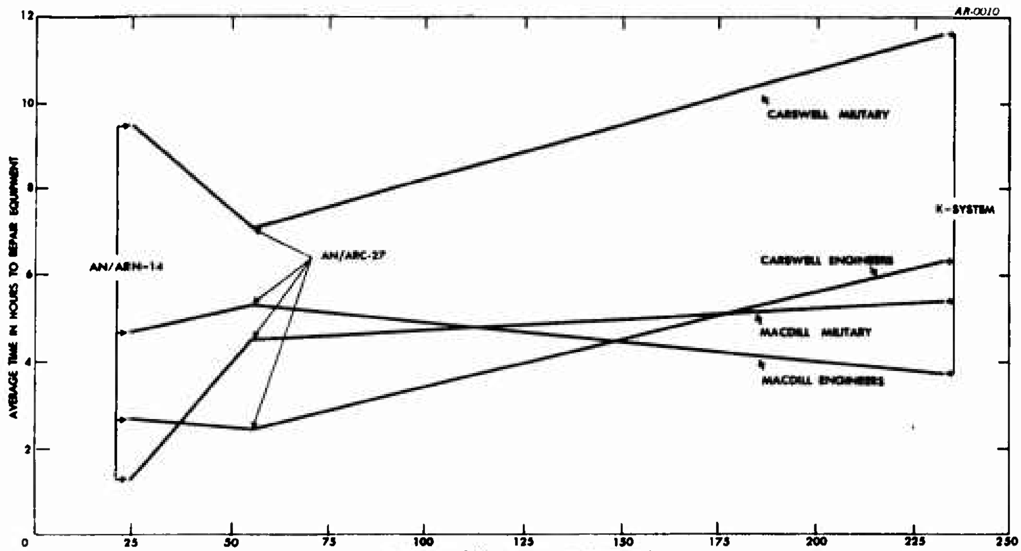

FIGURE 9
AVERAGE REPAIR TIME VS. COMPLEXITY OF EQUIPMENT: ENGINEER AND MILITARY MAINTENANCE AT CARSWELL AND MACDILL AIR FORCE BASES

A majority of the equipment repairs made by the military at Carswell were accomplished in the aircraft by flight-line maintenance men. On the other hand, a majority of the repairs at MacDill were performed in the shop. This was necessitated, in part, by the inaccessibility of the electronic equipment in the B-47 aircraft. Thus, military maintenance personnel at MacDill Air Force Base used an approach to equipment repair quite similar to that used by the engineers.

3.1.2 Tube Replacement, Part Replacement, and Adjustments

It is not unusual to find different maintenance groups using different approaches to equipment repair, even when the equipments are of the same type and the symptoms of failure are similar. Personal experience may suggest times when even the same man will use different approaches, on occasion, in an attempt to repair similar malfunctions. Two basic questions which arise from observations such as this are: (a) How is it possible that different maintenance actions seem to produce similar results -- that is, effectively repair an equipment? (b) Are the results actually similar?

To answer the second question first, the chances are that the results are not similar, although, as will be demonstrated in Section 3.3, the results of maintenance measured in terms of achieved equipment reliability do not demonstrate any consistent superiority of one type of maintenance over another. It is true, of course, that the data compiled from this test are in the nature of averages. A more meaningful test of different maintenance actions would be to determine equipment reliability after repairs of specific types of reported malfunctions, rather than to compare pooled data as has been done in the ARINC Research test. Unfortunately, sufficient data are not available from this test to permit such a comparison. If the data were taken at face value, the conclusion would be that alternative maintenance actions which are taken at many repairs do not materially affect measured equipment reliability.

There are two logical explanations for such a conclusion:

(a) For certain malfunctions, the repairman may have a choice between a temporary repair or a more permanent repair. Either action will lead to correction of the malfunction, although one may be better than the other.

(b) If repair of an equipment involves some degree of trial and error, as was suggested in Section 3.1.1.1, then some unnecessary maintenance actions (not really alternative repair actions) may be performed before the equipment is finally repaired.

While both of these processes could be in operation -- possibly concurrently at the same repair -- the hypothesis of trial and error is favored as being the most logical explanation.

In the following presentation of data concerning the observed frequency of maintenance actions taken at repair, it is assumed that any repair of an equipment might involve any one of the following types of maintenance actions:

(1) adjustment alone,

(2) tube replacement alone,

(3) replacement of parts (other than tubes) alone,

(4) adjustment and tube replacement,

(5) adjustment and other-part replacement,

(6) tube and other-part replacement, and

(7) adjustment plus tube and other-part replacement.

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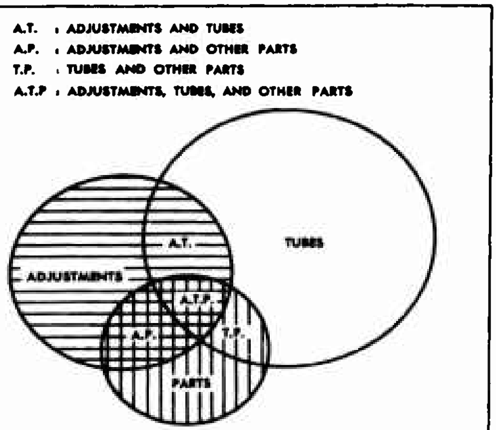

FIGURE 10

RELATIONSHIP AMONG ADJUSTMENTS, TUBE REPLACEMENTS, AND OTHER PART REPLACEMENTS

Figure 10 is an illustration of the relative proportions of the several types of maintenance actions -- the total area covered by the three circles being proportionate to the total number of repairs, and each subarea representing the proportion of repairs that included only the designated maintenance actions. As may be seen from Figure 10 and from the above list of maintenance actions, there are four mutually exclusive types of repair in which tubes may be replaced:

(1) tube replacement alone,

(2) adjustment and tube replacement,

(3) tube and other-part replacement, and

(4) adjustment plus tube and other-part replacement.

In the following presentation of data, the above four categories are condensed to two:

(1) tube replacement alone, and

(2) tube replacement and other maintenance action.

Similar condensed categories will be used in the discussion of other-part replacements and adjustments.

The term "repair", as used in this section, implies that either part replacement or adjustment was performed by the repairman on the basis of his assumption that the equipment needed repair. Routine tests of the equipment were excluded from the data unless part replacement or adjustment followed as a consequence of the test.

3.1.2.1 Replacement of Tubes

Table 6, based upon the total number of repairs made on the AN/ARC-27 equipments during the test, shows the percentage of repairs, by maintenance group, that included tube replacements. This table indicates a tendency on the part of military maintenance personnel to rely upon tube replacement more frequently than on any other type of action as a means of effecting equipment repair. The percentage of repairs in which tubes were replaced by military repairmen ranges from 48.2 percent at Norfolk Naval Air Station to 100 percent at Carswell Air Force Base. By contrast, the engineers replaced tubes in fewer than one-half of all repairs. This suggests that either the military technician was somewhat prejudiced against electron tubes -- perhaps because he believed tubes to be the dominant cause of equipment failure -- or he replaced tubes on the grounds that tube replacement was one of the simpler repair actions he could take. The engineer, on the other hand, was more judicious in his analysis of tubes, and, of course, he was influenced by the special instruction that he minimize tube replacements.

Of special interest in Table 6 is the high percentage of repairs that included "other repair actions" as well as tube replacements, and the relatively small percentage of repairs made by tube replacements alone. The implication would seem

TABLE 6 PERCENTAGE OF ALL REPAIRS THAT INCLUDED TUBE REPLACEMENTS: AN/ARC-27 EQUIPMENTS						
Type of Repair Action	AIR FORCE				NAVY	
	Carswell Air Force Base		MacDill Air Force Base		Norfolk Naval Air Station	
	Military	Engineer	Military	Engineer	Military	Engineer
Percentage of Tube Replacements Only	0 %	17.0%	15.6%	22.2%	20.0%	9.9%
Percentage of Tube Replacements with Other Repair Actions	31.0	83.0	43.8	19.5	28.2	25.3
Percentage of all Repairs with Tube Replacements	31.0	100.0	59.4	41.7	48.2	35.2

to be that only a small percentage of equipment failures (probably less than 25 percent) can be traced to tubes alone. Certainly it cannot be argued unequivocally that tubes were the sole cause of failure in those instances where tube replacement was accompanied by other repair action. In fact, a stronger argument would be that many of these tube replacements were useless maintenance actions.

3.1.2.2 <u>Replacement of Parts other than Tubes</u>

Table 7 summarizes the data concerning repair actions that included replacement of parts other than tubes.

In 5 of the 6 maintenance groups, there is a remarkable consistency in the percentages of all repairs that included parts replacement. The average value of parts replacement is approximately 35 percent; and in view of the consistency

TABLE 7 PERCENTAGE OF ALL REPAIRS THAT INCLUDED PARTS REPLACEMENTS: AN/ARC-27 EQUIPMENTS						
Type of Repair Action	AIR FORCE				NAVY	
	Carswell Air Force Base		MacDill Air Force Base		Norfolk Naval Air Station	
	Military	Engineer	Military	Engineer	Military	Engineer
Percentage of Parts Replacements Only	0%	26.2%	12.5%	19.4%	17.7%	25.3%
Percentage of Parts Replacements with Other Repair Actions*	0	11.9	21.9	16.7	14.1	15.4
Percentage of all Repairs with Other Parts Replacements	0	38.1	34.4	36.1	31.8	40.7

* The "other actions" were almost entirely tube removals.

within 5 of the 6 groups, the exception (military maintenance at Carswell Air Force Base) might be considered a chance event. It also should be noted that the 5 equipments maintained by military maintenance at Carswell Air Force Base operated the fewest number of hours and represent a total of only 12 repairs.

In the installation and conduct of the ARINC Research test, the engineers were given no special instructions concerning replacement of parts other than tubes; they were thus free to replace such parts at their own discretion.

Generally speaking, replacement of parts other than tubes is more difficult than tube replacement. The difficulty of replacement of parts such as resistors, capacitors, etc., discourages needless removal, while the ease of replacing tubes may facilitate and encourage tube removal. It may be argued that the percentage of other-parts replacement represented essential repair actions and thus could be expected to be consistent from one maintenance group to another. (The data show little evidence of prejudice against any particular part or class of parts, such as might exist in the case of tube removals. With the exception of dynamotors, which were removed in several repairs at Norfolk Naval Air Station and at MacDill Air Force Base, very few other parts were represented by more than one removal.)

The only area where engineers, as a class, seem to differ significantly from military maintenance personnel is in the percentage of repairs effected by parts replacement alone. Here the percentage is higher for the engineering groups than for the military. This is as would be expected, since, if the engineers made fewer repairs that included tube removals, they would make correspondingly more repairs that included the replacement of other parts.

TABLE 8

PERCENTAGE OF ALL REPAIRS THAT INCLUDED ADJUSTMENTS: AN/ARC-27 EQUIPMENTS

Type of Repair Action	AIR FORCE				NAVY	
	Carswell Air Force Base		MacDill Air Force Base		Norfolk Naval Air Station	
	Military	Engineer	Military	Engineer	Military	Engineer
Percentage of Adjustments Only	0 %	40.4%	18.7%	33.3%	34.1%	34.0%
Percentage of Adjustments with Other Actions	83.3	31.0	43.8	19.5	21.2	27.5
Percentage of all Repairs with Adjustments	83.3	71.4	62.5	52.8	55.3	61.5

3.1.2.3 Repairs by Adjustment

Table 8 shows, for each of the maintenance groups, the percentage of repairs made by adjustment of the equipments. Each group made adjustments in at least one-half of all repairs -- the proportion ranging from 52 to 83 percent. While there seems to be no consistent pattern of difference between engineering and military maintenance practices insofar as the over-all percentage is concerned, there does seem to be a fair amount of consistency among the engineering groups when the percentage of equipments repaired by adjustments alone is considered. The engineers apparently were able to repair about one-third of the equipments by adjustments only, while the military, in general, accomplished a smaller percentage of repairs by this means.

ARINC Research Corporation is of the opinion that the engineers would expend considerable effort to repair an equipment by adjustment alone in an attempt to minimize tube removals. Thus, the 30 to 40 percent of engineering repairs made by adjustments alone is probably an accurate reflection of the percentage of equipment malfunctions that can be repaired by adjustments. On the other hand, military personnel, who were not as concerned with conservation of tubes as were the engineers, may have attempted to repair equipments by tube substitution alone. In some instances, this procedure can compensate for a malfunction that could have been repaired by an adjustment.

3.1.2.4 Distribution of Minimum Repair Actions

From the data contained in Tables 6, 7, and 8, it is possible to construct -- as a crude estimate -- a table of minimum repair actions for AN/ARC-27 equipments. Such a table can provide a rough indication of the percentage of repair actions that would fall into each category of repair if military maintenance personnel, for example, did the absolute minimum in terms of the number of repair actions required to repair a failed equipment.

Table 9 compares the estimated minimum figures that have been prepared with the comparable percentages for the engineering and the military maintenance groups at MacDill Air Force Base. These groups were selected as being reasonably typical of the maintenance groups under observation in the field investigation.

TABLE 9

COMPARISON OF ESTIMATED MINIMUM REPAIR ACTIONS WITH TYPICAL MILITARY AND ENGINEER REPAIR ACTIONS

Type of Repair Action	Estimated Minimum Repair Actions (Percents)	Typical Military Maintenance (Percents)	Typical Engineering Maintenance (Percents)
Repair by Tube Removal Only	10 - 25%	15.6%	22.2%
Repair by Part Removal Only	30 - 40	12.5	19.4
Repair by Adjustment Only	30 - 40	18.7	33.3
Repair by Combination of Adjustment and Tube or Part Removal	5 - 20	53.2	25.1

The significance of the comparisons presented in Table 9 is fairly evident. Typical military maintenance underestimates the importance of adjustments and replacement of parts other than tubes, and tends to concentrate on tube replacement as the most effective way to repair the AN/ARC-27 equipment. The result is that tube removals in many instances represent wasted effort, and eventually the adjustment or other part replacement has to be made to repair the equipment, with a resultant high percentage of combined maintenance actions.

3.1.3 Tube Removals

After the source of the equipment malfunction has been localized to the circuit level, the next step in the repair process, which will lead either to part adjustment or substitution, is an investigation of the individual parts. If the malfunctioning part is visually obvious, such as a tube with a broken envelope or a burned-out filament, the repair process is relatively simple. When the malfunctioning parts are less obvious, the repair becomes more difficult. It would not be unreasonable in the less obvious case to find the repairman resorting to part substitution, and particularly to tube substitution, in an attempt to eliminate the source of the malfunction. The alternative approach is to undertake a difficult circuit analysis, which not only is time-consuming but requires that the repairman have considerable theoretical experience.

Since it is reasonable to expect a repairman to resort to some tube substitution at this final stage of repair, it is not unreasonable to expect that more than one tube will be removed at certain repairs. It is highly probable, also, that some of the tube removals will be unnecessary, in the sense that the tubes were not directly contributory to the cause of the equipment malfunction. This does not mean to imply that all repairs in which more than one tube was removed represent cases of unnecessary tube removal; certain situations exist where multiple tube removals are justified. The question is, what is the relative proportion of justifiable, multiple tube removals to unnecessary tube removals? This question probably will never be answered definitively, although evidence from the ARINC Research test suggests that unnecessary tube removals are a factor of considerable magnitude.

3.1.3.1 Valid Causes for Multiple Removals

Before an analysis of tube-removal practices is undertaken, it is useful to take note of some of the valid causes of multiple tube removal. These causes include the following:

(1) A tube failure that induces the failure of one or more other tubes -- for example, multiple failures of tubes in the same filament string have been observed in equipments where the failure of one tube filament caused an over-voltage to be applied to the other tubes.

(2) An external condition, such as a severe physical or electrical shock, that causes the failure of several tubes simultaneously.

(3) The gradual deterioration of several tubes that in time reaches the point of causing an equipment failure. It may be possible to repair the failure by replacing only one of the tubes, but in instances such as this it is a better practice to replace all of the tubes.

The ARINC Research field investigation was conducted in a manner that should have minimized unnecessary, multiple tube removals. New complements of tubes were installed in the equipments at the beginning of the investigation; and, during the time of test, very few equipments operated for a period sufficiently long to reach a point of general tube deterioration. Thus, it seems unreasonable to attribute many of the tube removals made in this test to general tube deterioration. However, at one base of operation, a few tube types did begin

to show signs of deterioration to the extent that they apparently had an effect upon equipment reliability (see pages 72-74 for an analysis of these removed tubes).

The data indicate few other instances of justified multiple tube removals. If the majority of multiple tube removals are necessitated because these tubes are the cause of equipment malfunction, then, in a comparative study of several maintenance groups engaged in the repair of similar equipments operated under similar conditions, one should expect to find a similarity in the number of tubes removed and in the frequency of certain classes of tube defects. This hypothesis was not sustained by the data obtained during this field test. Over the same period of equipment operating time, the engineers removed fewer tubes than did the military technicians, and the defect distribution of the tubes differed materially between the two groups.

3.1.3.2 Analysis of Unnecessary Removals

The data do not sustain a strong argument that the engineers made only necessary tube removals, and that removals by the military technicians which were in excess of the removals by engineers represent unnecessary tube removals. The indications are that the engineers, too, made some unnecessary removals. Twenty-six percent of the tubes removed from AN/ARC-27 equipments by the engineers and 46 percent of the tubes removed by the military technicians did not test defective when subsequently tested on laboratory-type equipment. While it is possible that laboratory tests may show a tube as being "good" -- and yet it will not work in the equipment -- one would not expect the proportion of such tubes to be as high as the 26 percent replaced by the engineers.

One factor contributing to the sizable proportions of tube removals that are satisfactory when tested on laboratory instruments is the lack of correlation between field tube-testing rejection criteria and military specification criteria on which laboratory analysis is based. Even where correlation may exist, the correspondence is seldom one to one -- field tube-tester rejection criteria are usually set very near the low limit for new tubes, with practically no allowance for deterioration. Thus, many field tube testers will reject tubes which are operating satisfactorily in equipment and which have many thousands of hours of useful life remaining.

In one sense, tubes which operated satisfactorily in the equipment but which were subsequently removed because of rejection by the tube-tester should not be classified as

having been unnecessarily removed by maintenance. The maintenance man in this situation is using the tube tester as a repair tool; the fault is in the tube-tester criterion, and not in the maintenance man. However, tubes such as these would be unnecessary removals in the sense that they did not contribute to the immediate equipment malfunction.

The fact that "tube-tester removals" can represent a considerable proportion of all tube removals was evidenced in this test by the high percentage of tubes which tested defective upon removal from AN/ARC-27 equipments that were operating satisfactorily. At the end of this test, all equipments were placed in satisfactory operating condition by the engineers. All tubes in these equipments were then removed and tested. (This test was made on the Weston Model 686 tube tester; for tube tests in the course of the investigation, either the Weston 686 or the Hickok Model 539A tester was used.) The percentage of tubes judged defective by the laboratory tests, after having been found in satisfactory operating condition in AN/ARC-27 equipments at the termination of the test, is shown in Table 10. No comparable data on the field tube testers is available, but previous experience would indicate the expected percentage to be higher. The point to be emphasized is that whenever one chooses to test a sizable proportion of the tubes in an equipment, a rather large number of "tester" defectives having very little to do with proper equipment operation can be found.

TABLE 10

PERCENTAGE OF DEFECTIVE TUBES REMOVED FROM OPERATIVE AN/ARC-27 EQUIPMENTS AT TERMINATION OF TEST

Type of Maintenance	Percentage of Defective Tubes Removed by Test Base		
	Carswell Air Force Base	MacDill Air Force Base	Norfolk Naval Air Station
Military	36%	31%	25%
Engineer	52	45	35

Most of the other types of equipment in the test did not contain as high a percentage of defective tubes as did the AN/ARC-27 equipments. However, the other types of equipments generally did not operate for as long a period of time; thus there was less chance of a tube becoming defective.

An interesting feature of Table 10 -- in addition to the rather startling percentage of defective tubes tolerated by the AN/ARC-27 equipments -- is that each base comparison shows a smaller percentage of defective tubes in the

military-maintained equipments than in the engineer-maintained equipments. This situation, however, would be expected in view of the fact that the engineers removed fewer tubes during the test than did the military technicians. The engineers reported that they relied very little upon the tube-tester criterion for tube removal; their usual approach was to substitute a known good tube for a suspected one. If the substitute tube did not correct the equipment malfunction, the original tube generally was returned to the socket. When such a technique is used, it is not surprising to find that operating equipments contain some tubes which test defective on a tube checker. While the military technicians may have used tube substitution as well as the tube tester, they apparently made less effort to return the original tubes to the equipment when the substitute tubes did not correct the malfunction. As a consequence of this higher tube-replacement rate, fewer "tester-defective tubes" were found in the equipments maintained by the military technicians at the termination of the test.

Another fact which is obvious from the high percentage of tubes found to be defective at the termination of the test is that, during this test, neither maintenance group made systematic searches of the entire equipment during repair for tubes which might test defective. If they had, the number of tubes removed during the test would have been much higher and the proportion of defective tubes found at termination much lower. This observation suggests that most repairs are localized to a fairly small number of parts within the equipment and that part substitution is restricted to these few parts.

The fact that a tube tester will detect certain defective tubes which the equipment might tolerate implies that certain types of tube defects are more detrimental to equipment operation than others. While a tube removed because it tests defective on the tube tester may not be an unnecessary removal, the indication is that some of these removals are less necessary than others. Information on the less serious types of tube defects is provided by Table 11, which shows the percentages of the various types of tube defects found at the end of the test in the operating AN/ARC-27 equipments.

From the data contained in Table 11, it is apparent that the AN/ARC-27 equipment is quite tolerant to tubes which are outside electrical limits (Code 500) and reasonably tolerant to some tubes in the shorts-and-opens defect category (Code 300-400). It is believed that most of the tubes in the 300-400 defect class, when tested on the tube tester, appeared

TABLE 11

PERCENTAGE OF TUBES REMOVED BY TUBE DEFECT AT TERMINATION OF TEST: ENGINEERING AND MILITARY MAINTENANCE

Type of Maintenance	Percentage of Defective Tubes by Category of Defect*					
	001 100	200	300 400	500	600 700	Total
Military	0	0	11	86	3	100%
Engineer	0	0	11	85	4	100%

* Tube Defect Code

001 - 100: Mechanical defects and envelope defects.
200 : Defective filament or heater.
300 - 400: Shorts and opens.
500 : Outside electrical limits.
600 - 700: Grid currents.

to have short circuits; but, in reality, these were tubes with low interelectrode resistance, which caused them to test as shorted tubes.

Some of the tubes removed during repairs of the AN/ARC-27 equipments had defects of the type to which the equipment is quite tolerant -- i. e., they were "tube-tester defectives" only. When all of the tubes removed during the test are separated into two classes -- (1) those in which only one tube was removed at a repair, and (2) those in which more than one tube was removed at a repair -- it is not particularly surprising to find the multiple-tube-removal class to be dominated by the less detrimental types of tube defects. The distribution of defects for removals in both classes is shown in Table 12. These data imply that the removal of tubes with the less serious defects will not correct the immediate cause of equipment malfunction. If tubes are the cause of the malfunction, a tube with another type of defect generally will have to be removed before the malfunction is corrected -- hence, the multiple removals. Conversely, malfunctions corrected by the removal of only one tube will tend to be of the type in which a tube was at fault and the nature of the tube defect was detrimental to equipment operation. Among these single removals, defects are predominantly of the mechanical or catastrophic types (Code 001-200) and fewer tubes fall in the outside-electrical-limits category (Code 500).

TABLE 12

DEFECT DISTRIBUTIONS OF SINGLE AND MULTIPLE TUBE REMOVALS FROM AN/ARC-27 EQUIPMENTS: ENGINEERING AND MILITARY MAINTENANCE

Type of Maintenance	Type of Tube Removal	Tubes in Each Defect Category*											
		001-100		200		300-400		500		600-700		Total	
		No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Military	Single	7	43	0	0	4	25	2	13	3	19	16	100
	Multiple	25	12	2	1	59	28	90	43	34	16	210	100
Engineer	Single	6	26	2	9	6	26	4	17	5	22	23	100
	Multiple	7	9	0	0	28	35	31	39	14	17	80	100

* Tube Defect Code

001 - 100: Mechanical defects and envelope defects.
200 : Defective filament or heater.
300 - 400: Shorts and opens.
500 : Outside electrical limits.
600 - 700: Grid currents.

Table 12 is of further interest in that it presents evidence of the effects of tube handling upon tube removals from AN/ARC-27 equipments. One of the original hypotheses in the investigation was that if military technicians handle tubes excessively, they run a greater risk of damaging the tubes by handling alone. The data in Table 12 appear to bear out this hypothesis.

A total of 32 tubes removed by military technicians were found, on laboratory investigation, to have either glass or mechanical defects. Seven of the tubes were from repairs in which a single tube was removed; the remaining 25 were from repairs in which multiple tube removals occurred. Of the tubes removed by engineers, on the other hand, 13 were in the classification of glass and mechanical damage; and of this total, 6 were from repairs in which a single tube was removed, while 7 were from repairs involving multiple removals.

For the two types of maintenance, the overall proportion of glass and mechanical defects is almost the same: 32 out of 226 tubes (14.2 percent) for the military and 13 out of 103 tubes (12.6 percent) for the engineers. It seems reasonable to assume that roughly 12 to 14 percent of the total tube removals are attributable to glass or mechanical defects, and that a large proportion of these defects are caused by handling of the tubes, including the acts of removal from the socket, insertion, and re-insertion. On the basis of this

assumption, the difference in the total number of tubes with glass and mechanical defects (19 tubes) can be attributed to the unnecessary removal of tubes by the military technicians and the attendant increased tube handling. The military technicians removed a total of 226 tubes from AN/ARC-27 equipments during the test; thus, if the premises stated above are accepted, 8.5 percent of the tubes removed by the military technicians can be considered to have been damaged by excessive handling.

From the data obtained in this test, it can be concluded that some tubes are unnecessarily removed; that, as a minimum, the unnecessary removals include those tubes removed by the military technicians in excess of tubes removed by the engineers; and that some of the tubes removed, even though they test defective on the tube tester, do not have defects of the serious type and do not contribute directly to the cause of equipment malfunction.

3.1.3.3 Minimum Removals for AN/ARC-27 Equipment

The observations in Section 3.1.3.2 suggest the following basic question: What is the minimum number of tube removals that can be considered essential for repair of the AN/ARC-27 equipment? If one considers only the equipment operating time that accumulates before mass tube deterioration begins to take effect, a logical answer to this question may be derived from analysis of engineering maintenance of the AN/ARC-27 equipment at Norfolk Naval Air Station.

In the engineering segment of the test at Norfolk Naval Air Station, 9 tubes were removed during 8 repairs of 5 different AN/ARC-27 equipments, which had operated a total of 400 hours each. Tube removals occurred in all of the repairs. There are 55 tubes in each AN/ARC-27 equipment, or a total of 275 tubes in 5 equipments; thus, the tube-removal rate for these 5 equipments was 3.27 percent at 400 hours of operation, or 0.82 percent for each 100 hours of operation. In the military segment of the test at Norfolk, 22 tubes were removed during 100 repairs of 5 different AN/ARC-27 equipments, each of which had operated a total of 400 hours. Again, tube replacements occurred in all of the repairs. Therefore, the tube-removal rate for the military technicians was 8.0 percent at 400 hours of operation, or 2.0 percent for each 100 hours of operating time.

The foregoing data show that the military technicians made 2 more repairs and removed 13 more tubes from the 5 equipments than did the engineers; these 13 additional tubes

removed by the military may be considered as an estimate of non-essential tube removals. When these figures are converted into average values, it can be said that the engineers removed an average of 1.12 tubes per repair that included tube replacements, while the military technicians removed an average of 2.2 tubes per repair. Therefore, the estimated average of tubes unnecessarily removed by the military is one tube at each repair that included tube replacement.

All tubes under consideration in the foregoing example met the qualification of having operated less than the number of hours in which general deterioration might be expected to become serious. This general deterioration point was estimated by the engineers at Norfolk to occur at about 400 hours of operation for certain tube types -- particularly the 6J4, the 12AT7, and the 6AG5. After 400 hours of operating time, the engineers permitted greater freedom in the replacement of these tube types. The more liberal replacement of tubes from this point in the test to its conclusion was more indicative of preventive maintenance than of corrective repair actions. The engineers were attempting to improve equipment reliability by eliminating possible causes of future failures, and were not merely removing tubes to correct existing malfunctions.

3.1.3.4 Hypothetical Bases for Unnecessary Multiple Removals

The preceding example from the Norfolk Naval Air Station suggests that only infrequently will more than one tube need to be removed to effect the repair of an AN/ARC-27 equipment. Where more than one tube is removed, the additional removals may be considered less essential to the actual repair.

In view of this evidence, it is desirable to obtain, if possible, an explanation of the tendency to attempt equipment repair by multiple tube removals. Several hypotheses might be formulated to account for this tendency, and the true reason might be, of course, any one of these possible explanations or some combination of them. The most obvious hypotheses are:

(a) When logical diagnosis has reached a certain point at the circuit level, it may appear more expeditious to attempt the final isolation of the trouble spot by trial-and-error tube substitution.

(b) Once the source of trouble has been located and a repair has been effected, accessible tubes within the immediate vicinity are tested as a preventive maintenance measure.

(c) Where several tubes are closely associated in a single function with highly interacting circuitry, replacement of all tubes in this single function may be desirable since a truly single cause of failure may not exist.

It is not possible to test all of these hypotheses by means of the available data, nor is it possible at this time to establish definitely which of the hypotheses actually explains the tendency toward multiple tube removals. Nevertheless, further analysis shows the data to be consistent with a necessary deduction resulting from the trial-and-error hypothesis.

For the purposes of the analysis, it will be assumed that the trial-and-error hypothesis is correct, and that only one tube is really at fault in an individual repair. The probability of replacing the faulty tube on the first trial will be denoted by p, and the probability of replacing the wrong tube at any single trial by $q = 1 - p$. Then, the probability that n tubes will be removed during a repair is the probability of replacing $n - 1$ tubes which are not the cause of malfunction followed by replacement of the faulty tube on the n^{th} trial. This probability is

$$p(n) = q^{n-1}p \qquad n = 1, 2, 3, \ldots \quad . \tag{2}$$

Now, if M repairs are made that involve some tube replacements, the expected number of repairs involving exactly n tube replacements is

$$Mq^{n-1}p. \tag{3}$$

The value of the single unknown parameter, p, is estimated from the sample data by the reciprocal of the average number of tubes removed per repair. As an example, if an average of three tubes is removed per repair, the chance that the right tube is removed at a single trial is 1/3.

It is now interesting to examine the actual number of repairs which involve a given quantity of removed tubes in relation to the number predicted by the deduction from the trial-and-error hypothesis. The comparison is shown in Table 13. While the number of repairs is too small to yield a highly meaningful result from a goodness-of-fit test (even though such a test shows a non-significant difference between observed and theoretical frequencies), it is surprising that

TABLE 13

COMPARISON OF NUMBERS OF EXPECTED AND OBSERVED REPAIR ACTIONS THAT INCLUDED TUBE REMOVALS

Number of Tubes Removed per Repair	AIR FORCE								NAVY			
	Carswell Air Force Base				MacDill Air Force Base				Norfolk Naval Air Station			
	Military		Engineer		Military		Engineer		Military		Engineer	
	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
1	5	5.1	10	9.9	4	5.5	9	9.4	6	4.2	7	7.1
2	4	3.0	4	3.8	3	3.9	4	3.5	1	2.4	1	0.8
3	-	1.7	-	1.4	5	2.8	1	1.3	-	1.4		
4	2	1.0	2	0.6	3	2.0	1	0.5	1	0.8		
5	-	0.6			2	1.4			-	0.5		
6	-	0.3			-	1.0			2	0.3		
7	1	0.2			1	0.7						
8					-	0.5						
9					-	0.4						
10					-	0.3						
11					-	0.2						
12					1	0.1						

the fit is as close as the table shows it to be. At the very least, it can be said that the data are consistent with a necessary logical consequence of the trial-and-error hypothesis.

Probably the most striking comparison made in Table 13 is in the number of tubes removed by the engineers and the military repairmen. Here is a definite illustration of the tendency of the military technician to remove more tubes during a repair than does the engineer. If we assume the trial-and-error hypothesis to be correct, there is the further implication that the engineer, as opposed to the military technician, carries logical trouble-shooting down to a much smaller region before resorting to trial-and-error techniques. The quantities of tubes removed at a single repair by the military technicians are in many instances quite large; for example, Table 13 shows 12 tubes removed at a single repair at MacDill AFB. This particular instance represents nearly a 25-percent turnover of the entire tube complement in the AN/ARC-27 equipment. The engineers appear

to have been reasonably successful in restricting the number of tubes replaced during a single repair to 4 or less. It is reasonably certain, however, that instructions to the engineers to conserve tubes was an important factor in their limited removals, and could well explain efforts to carry logical methods of trouble-shooting to the limit of their usefulness.

When one considers the difficulties involved in localizing a malfunction to a specific tube by logical signal-tracing methods -- without actually removing the tube from the socket -- and the relative ease with which a known good tube can be substituted for a suspected one, additional credence of an entirely independent nature can be attributed to the trial-and-error hypothesis.

The distribution of tube removals at Norfolk Naval Air Station is of special interest in this analysis. The data in Table 14 represent only repairs made during the first 400 hours of equipment operation, when the tubes were all relatively new. Table 15 shows the experience after 400 hours, in the period when the engineers' criterion was changed from that of maximizing tube life to one which would maximize equipment reliability.

It is obvious from Tables 14 and 15 that the relaxation of the minimum tube removal criteria had an effect upon the quantity of tubes removed during engineering maintenance. In this second interval of the test, engineering maintenance was not appreciably different from military maintenance, if judged by tube removals alone. A difference in objectives must be assumed, however, since the action taken by the engineers was carefully considered and based upon a knowledge of the age of the tubes in the equipment, while the military personnel were uninformed of the age of the tubes. An interesting finding is that, as the equipments aged, military maintenance techniques also changed in the direction of larger quantities of tubes removed per repair. In Section 3.3, a more detailed analysis will be made of the engineers' decision, based on the wear-out argument, to remove more tubes from the older equipment.

The arguments presented in the foregoing paragraph, and the data comparisons associated with them, are not wholly consistent with the trial-and-error hypothesis alone, if it is assumed that the engineers continued their previous emphasis on logical trouble-shooting as a means of finding a specific trouble. This assumption would not lead to a change in the expected number of tube removals or the probability of success on a given trial (p). If the assumption is retained,

TABLE 14 NUMBER OF REPAIRS THAT INCLUDED TUBE REMOVALS PRIOR TO 400 HOURS OF OPERATION: AN/ARC-27 EQUIPMENTS AT NORFOLK NAVAL AIR STATION				
Number of Tubes Removed per Repair	Military		Engineer	
	Obs.	Exp.	Obs.	Exp.
1	6	4.2	7	7.1
2	1	2.4	1	0.8
3	-	1.4		
4	1	0.8		
5	2	0.3		
6				
7				
8				
9				
10				

TABLE 15 NUMBER OF REPAIRS THAT INCLUDED TUBE REMOVAL FROM BETWEEN 400 AND APPROXIMATELY 900 HOURS OF OPERATION: AN/ARC-27 EQUIPMENTS AT NORFOLK NAVAL AIR STATION				
Number of Tubes Removed per Repair	Military		Engineer	
	Obs.	Exp.	Obs.	Exp.
1	11	9.5	8	7.4
2	7	6.7	3	5.1
3	5	4.7	5	3.5
4	-	3.3	2	2.5
5	1	2.3	3	1.7
6	2	1.6	2	1.2
7	-	1.1	1	0.8
8	4	0.8		
9	1	0.6		
10	1	0.4		

Equation 3 cannot possibly explain both Table 15 and 16; yet the fit between the observed data and the expected values is still fairly good in Table 15. This is true even though replacements of 3, 4, 5, and 6 tubes at a time do seem to occur more frequently than might be expected.

To account for the noted change without requiring a basic change in the engineers' diagnostic abilities or methods, it can readily be argued that the second hypothesis is really true for the case represented by Table 15. This hypothesis was: "Once the source of trouble has been located and a repair has been effected, accessible tubes within the immediate vicinity are tested as a preventive maintenance measure." It is quite conceivable that the mathematical consequences of this hypothesis could be so close to Equation 3 that the correct equation could not be discerned from the fit of the limited data available.

Despite the possible ambiguity in cause-and-effect relationships responsible for multiple tube removal, Equation 3 nevertheless seems to fit the observed data reasonably well, and it is quite logical to summarize all tube removal data in terms of the parameter of this equation. The value of the parameter, p, is estimated from sample data by the reciprocal of the average number of tubes removed per repair that included tube replacement. Thus, from the information

regarding the average number of tubes removed at a repair and the total number of repairs that included tubes, it is possible to obtain a fair estimate of the number of repairs that included any given number of tube removals. Table 16 shows the average number of tubes removed per repair that included tube replacement during this test, and, as additional information, the percentage of repairs that included tube replacements is also shown.

Table 16 shows that, in all but two instances (the AN/APS-38A and the AN/URR-13), the military technicians made a higher percentage of repairs that included tube removals and removed more tubes at a repair, on the average, than did the engineers. For the engineers, the average number of tubes removed remains remarkably consistent, in the range of 1.6 tubes per repair. The rate for the military technicians is somewhat more variable, with an over-all average of about 2.4 tube removals per repair.

It also appears from Table 16 that the number of tube sockets in an equipment apparently bears little relationship to the percentage of repairs which include tube replacements or to the average number of tubes removed per repair. This observation suggests that the maintenance technicians did localize the cause of malfunctions to a fairly small portion of the equipment, regardless of whether the equipment had many tube sockets or few. If tube replacements were restricted to only this portion of the equipment, then one could reasonably expect the average number of tubes removed to be approximately constant from one equipment type to another.

Of particular interest is the average number of tubes removed by the engineers from the AN/ARC-27, AN/APS-31, and AN/APS-38A equipments. The test history for these three equipment types is essentially the same, with the exception that the AN/APS-31 equipments were phased out of the test at approximately 400 hours of operation and their entire tube complements were transferred to the AN/APS-38A equipments. The time of transfer was approximately the time when the engineer changed his test criterion to maximize equipment reliability. In Table 16, the effect of this change in policy is evidenced by the increase in the average number of tubes removed.

The analysis of the data from this test furnishes convincing proof that many tube removals are not absolutely essential to the repair of the equipment. Only infrequently is it necessary that more than one tube be removed at a repair -- at least until the time is reached when tube deterioration becomes a major problem. When tubes do begin to

TABLE 16

SUMMARY OF TUBE REMOVAL DATA

Equipment Type	Number of Sockets	Test Base*	Percent of Repairs with Tube Removal		Average Number Tubes Removed per Repair		Remarks
			Military	Engineer	Military	Engineer	
AN/ARC-27	55	CAFB	100	31	2.33	1.62	----
		MAFB	59	42	3.03	1.67	----
		NNAS	42	32	3.20	1.12	Equipments operated less than 400 hours.
		NNAS	58	43	3.38	2.95	Equipments operated beyond 400 hours.
R-252/ARN-14	25	CAFB	63	50	2.40	1.00	----
		MAFB	0	0	0	0	Military: No repairs. Engineer: No tube replacements in 6 repairs.
R-540/ARN-14	25	MAFB	40	0	1.00	0	Military: 2 repairs in 5 included tube replacements. Engineer: Total of 15 repairs; no tubes removed.
K-System	233	CAFB	47	35	2.37	1.73	----
		MAFB	42	28	1.97	1.54	----
AN/APS-31	124	NNAS	26	18	2.36	1.14	Equipments operated less than 400 hours.
AN/APS-38A	185	NNAS	33	60	1.64	1.97	Equipments operated more than 400 hours.
AN/URR-13	23	N(Ships)	9	13	1.00	1.56	Military: Based on only one repair that included tube replacement.
TED-3	16	N(Ships)	58	20	2.[illegible]1	1.27	
AN/PRC-6	13	Infantry, EUCOM	61	29	2.52	1.48	----
AN/PRC-10	11	Infantry, EUCOM	42	24	2.61	1.75	----
AN/GRC-4	56	Armored, EUCOM	76	42	4.11	1.83	----

*Legend

CAFB - Carswell Air Force Base
MAFB - MacDill Air Force Base
NNAS - Norfolk Naval Air Station
N(Ships) - Norfolk Naval Station (Ships)

Infantry, EUCOM / Armored, EUCOM — Infantry and Armored divisions at Wurzburg and Bad Kreuznach, Germany, respectively.

deteriorate, some multiple removals can be justified and may even be advisable. However, such removals should be made on the basis of a carefully considered plan, which takes into account the wear-out characteristics of the tubes and gives proper weight to the cost of replacement relative to the consequences of possible future failure. Multiple removals should not be undertaken on a hit-or-miss basis, as the current practice seems to be.

As part of a separate study, ARINC Research Corporation has made a thorough analysis of the optimum time for replacement of deterioration failures.* The results of the study included the following important findings:

(a) Operating costs, with proper inclusion of unscheduled failure costs, can be minimized by the proper selection of the time intervals for preventive replacements.

(b) Preventive replacements made at the wrong time can actually maximize costs.

3.2 <u>How the Maintenance Man Affects Tube Reliability</u>

Previous studies of tube reliability generally have led to the conclusion that tube-failure rates were constant with time; however, in some instances the conclusion has been the qualified one that possibly the failure rates were constant only for the period of time observed, and, that if the observations had been continued in time, the failure rates might not have remained constant. One of the common explanations advanced for the constant failure rates has been that there are many different causes of tube failure and that each of these causes could have a different time of occurrence. On the basis of this explanation, the argument has been that the nature of failure or time of failure is essentially unpredictable -- i. e., since no type of failure was dominant, no specific time to failure predominated. Because of the variety of failures and times to failure, the expectation would be for a constant chance of tube failure at any time.

It is believed this argument has considerable merit but ignores one important factor: tube reliability based on tubes used in field equipments is determined by the time the

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* Dr. E. L. Welker, <u>Relationship Between Equipment Reliability, Preventive Maintenance Policy, and Operating Costs</u>, ARINC Research Monograph No. 7, February 13, 1959, Publication No. 101-9-135.

tube operates in the equipment until it is removed, not necessarily the time until it has failed. If a maintenance man arbitrarily removes a tube, then field-derived tube reliability will reflect the time to removal, not the time to failure. Since trial-and-error tube substitution can and does take place, then some tube removals are arbitrary. This means that tube reliability determined from field experience depends upon the maintenance man; the expected life of a tube is the average time to removal, which can only be less than or equal to the average time to tube failure.

Since, in this test, the engineers were instructed not to make unnecessary tube removals, the tube reliability functions derived from engineering maintenance can be used as a basis for comparison of reliability based on tube failures. Military maintenance, on the other hand, furnished the typical picture of reliability based on tube removals. The comparison of engineering and military maintenance shows that the rate of tube failure generally is not constant while the rate of tube removal generally is constant.

The data suitable for presentation as tube reliability functions are limited in this test. It is not desirable to pool the data from different types of tubes or from different equipments, because pooling introduces unwanted variability in the reliability functions and it then becomes more difficult to determine the effects of maintenance. The data which are presented from this test are from the 6J4WA tubes used in the AN/ARC-27 equipments and from the 4X150A tubes used in the TED-3 equipments. The choice of these two types permits interesting comparisons of the several maintenance groups that used the AN/ARC-27 and the TED-3 equipments, and it also permits comparison of the maintenance of aircraft and shipboard equipments. These particular tube types have been selected because their lives are relatively short in comparison with other types, and thus, although the equipments in this test were in operation for a relatively short period of time, a considerable portion of the life history of these tubes can be examined. In order to extend the life history of tubes -- and also to examine another type of maintenance not encountered in this test -- an example of tube reliability drawn from ARINC Research experience at Station WAR is included.

3.2.1 The 6J4WA Tube Type in the AN/ARC-27 Equipment

Figures 11 and 12 show the reliability functions for the 6J4WA tubes used in the AN/ARC-27 equipments under surveillance in the ARINC Research field test. It is evident from

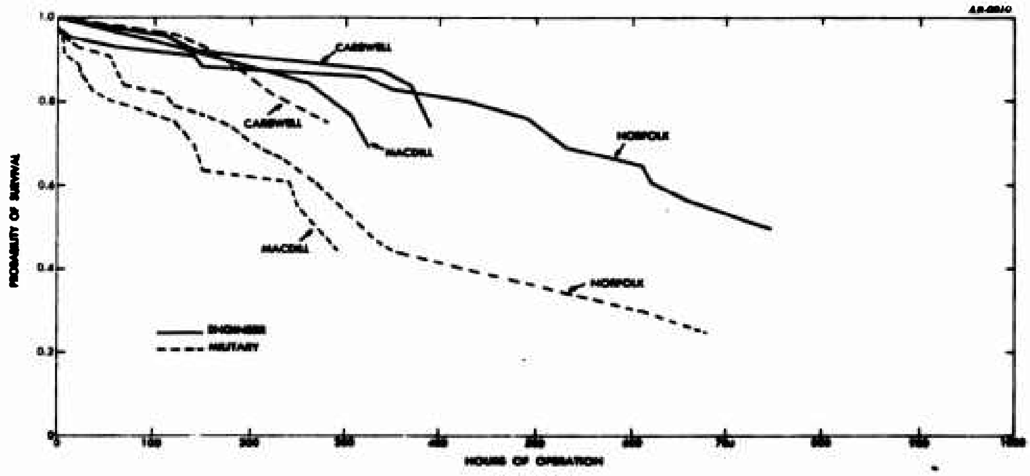


FIGURE 11
ENGINEERING VS. MILITARY MAINTENANCE: OBSERVED RELIABILITY FUNCTIONS
FOR TUBE TYPE 6J4WA IN AN/ARC-27 EQUIPMENTS AT THREE BASES

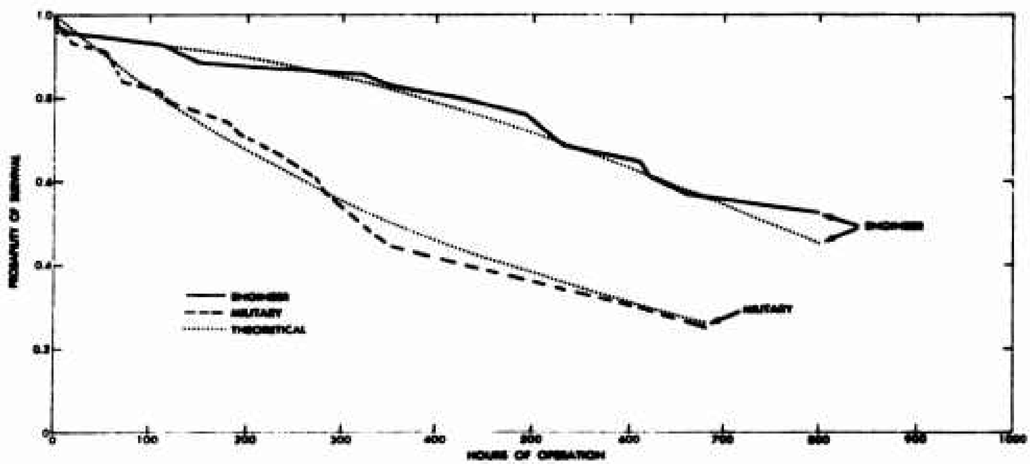


FIGURE 12
ENGINEERING VS. MILITARY MAINTENANCE: OBSERVED AND THEORETICAL RELIABILITY FUNCTIONS
FOR TUBE TYPE 6J4WA IN AN/ARC-27 EQUIPMENTS AT NORFOLK NAVAL AIR STATION

the comparison of engineering and military maintenance at the three bases that the reliability functions generated by engineering maintenance tend to be quite similar, while the reliability functions for military maintenance tend toward greater variability. Generally, the probability that a tube will survive engineering maintenance is better than is the probability it will survive military maintenance.

The configurations of the reliability functions for the 6J4WA tubes are of particular interest. All of the reliability functions generated by engineering maintenance tend to be concave downward. This trend indicates the probability of an increase in tube removals (failure) as the tubes become older. The reliability functions generated by military maintenance at MacDill and Norfolk tend to be concave upward, which corresponds to the situation in which tube-removal rates remain constant with increased tube age. Military maintenance is more nearly comparable to engineering maintenance at Carswell Air Force Base than at the other military bases.

Figure 12 demonstrates the major hypothesis of this section: tube failure rates increase with time; however, tube removal rates -- if replacement is dominated by trial-and-error tube substitution -- tend to remain constant. The consequence of this hypothesis is that the average life of a tube based on time to removal is less than the average life of a tube based on time to failure.

If one assumes that the rate of tube removal by military maintenance remains constant with operating time, the appropriate theoretical reliability function for these tubes would be an exponential of the form,

$$R(t) = e^{-t/\theta} \quad ;$$

and the configuration of the reliability function for engineering maintenance might be assumed to be determined by the Gaussian distribution. In Figure 12, the reliability functions for tube-removal experience at Norfolk Naval Air Station show agreement between the theoretical exponential and Gaussian assumptions for military and engineering maintenance, respectively.

If one assumes that when a reliability function is concave upward the exponential reliability function holds, and that when it is concave downward the Gaussian function holds, it is possible to estimate the expected life of tubes. The expected values for the 6J4WA tubes for each maintenance group at the respective test installations are shown in Table 17.

TABLE 17 ESTIMATED LIFE EXPECTANCY OF TUBE TYPE 6J4WA IN AN/ARC-27 EQUIPMENTS*			
Type of Maintenance	Estimated Life Expectancy in Hours		
	Carswell Air Force Base	MacDill Air Force Base	Norfolk Naval Air Station
Military	390	440	510
Engineer	660	480	750

* The values in the table were estimated graphically by plotting the MacDill and Norfolk military maintenance reliability functions on semi-log paper and taking the estimate of the mean at the 37 percent survival probability. The other expected lives were obtained by plotting the reliability functions on normal probability paper and estimating the mean at the 50 percent survival point. Straight-line fits were used.

Although the differences in the expected life of the tubes illustrated in Table 17 are not great, the engineers generally were successful in increasing the life expectancy of the tubes; therefore, it is believed engineering removals should more nearly correspond to time of failure.

3.2.2 The 4X150A Tube Type in TED-3 Shipboard Equipments

Figure 13 presents the reliability functions for the 4X150A power tubes used in the TED-3 shipboard transmitter. Isolation of causes of malfunction in this equipment is considered to be somewhat more simple than in AN/ARC-27 equipments, because most malfunctions are isolated to either the 4X150A tube or to the blower motor. Aboard ship, adequate test apparatus was not available to permit testing of the 4X150A tubes; thus the evaluation of these tubes was made in terms of equipment performance. The engineer refined the tube trouble-shooting procedure by substituting a known good 4X150A tube for the suspected tube. If the good tube failed to correct the equipment malfunction, the original tube was reinstalled. If the substitute did correct the malfunction, the new tube was used as a replacement for the old one. Insofar as is known, military maintenance personnel did not reinstall the suspected 4X150A tubes in cases where equipment performance was not improved by tube substitution. The

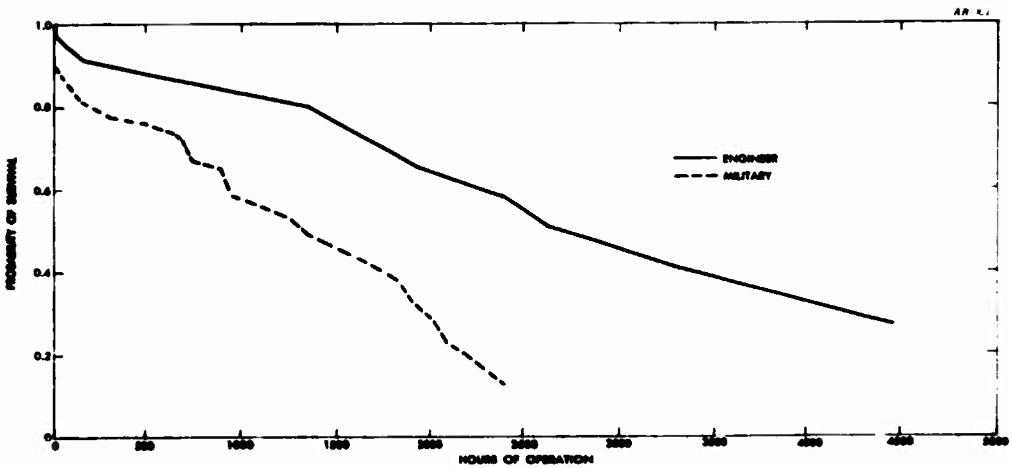


FIGURE 13
ENGINEERING VS. MILITARY MAINTENANCE: OBSERVED RELIABILITY FUNCTIONS FOR TUBE TYPE 4X150A IN TED-3 SHIPBOARD EQUIPMENTS

comparative results of the engineering and military maintenance policies are illustrated by the reliability functions in Figure 13.

Table 18 presents the estimated life expectancy of the 4X150A tubes used in the TED-3 shipboard transmitters. The tubes in the equipments that were maintained by engineering maintenance personnel had twice the life expectancy of those in equipments maintained by military personnel, although the extended life of the tubes in the engineer-maintained equipments was somewhat at the expense of "nursing" the tubes along. Whether or not such care is justified becomes purely a matter of economics. The 4X150A tube costs about 20 dollars. In terms of prorated initial tube costs, the military operated the tube at about 14 dollars per 1000 hours, while the cost for engineering operation was about 5 dollars per 1000 hours. In addition, the ship would need to supply more tubes for military maintenance than for engineering maintenance. On the other hand, one can ask the question, "Is the additional time spent in isolating the cause of equipment malfunction by the method of good-tube substitution, as used by the engineers, worth the extra time which might be spent on other repairs or maintenance actions?"

TABLE 18 ESTIMATED LIFE EXPECTANCY OF TUBE TYPE 4X150A IN TED-3 SHIPBOARD EQUIPMENTS	
Type of Maintenance	Estimated Life Expectancy in Hours
Military	1407
Engineer	3878

It is noteworthy that, while the average life of the tubes differed for the two maintenance groups, the configurations of the reliability-functions are quite similar. Neither curve shows a definite trend toward a single time of wear-out. This suggests that either there are multiple mechanisms of tube failure which tend to make failures independent of time, or that the predominant mechanism of failure is not particularly predictable in terms of operating hours.

During the period of this test, the major problem limiting the life of the 4X150A was the formation of leakage paths between electrodes across the glass base. When the tube is operated in standby condition, the conductance of the leakage paths increases progressively. Under actual transmitting conditions, the relatively high RF voltages applied tend to reverse the process, and the conductance of the leakage paths may erratically decrease. The combination of these phenomena may change the time-to-failure probability distribution from the Gaussian, which would be expected on the basis of increasing leakage path alone, to one in which the failure rate is practically constant -- i. e., exponentially distributed.

3.2.3 Tube Reliability in the R-390/URR Equipment

In a special test conducted at Station WAR, employing R-390/URR equipments operated nearly continuously, two types of maintenance policies were examined.* One was the standard

* Reported in Effects of Maintenance Techniques on the Reliability of Fixed Communication Equipment, Aeronautical Radio, Inc., Washington, D. C., February 1, 1958, Publication No. 111.

maintenance policy of mass-testing all tubes on a Hickok 593A tube tester each quarter-year, and the other was a modified maintenance policy in which mass tube-testing was discontinued and tubes were replaced only if they had an adverse effect upon equipment performance. The effects of these two types of maintenance on tube types 12AU7 and 6082 are shown in Figures 14 and 15, respectively.

In Figure 14, the reliability functions for tube type 12AU7 illustrate quite plainly the effect a particular type of maintenance can exert upon tube reliability. The steps in the standard tube reliability function correspond to the quarterly maintenance checks (a quarter of a year represents about 2200 hours of equipment operation). At these times, large quantities of tubes were removed because they tested defective. However, the modified maintenance reliability function shows that, if the criterion of satisfactory equipment operation had been used, these tubes need not have been removed. On the other hand, Figure 15 shows very little difference between modified and standard maintenance. In this instance, the tubes began to fail before the quarterly check. The curves in Figure 15 also suggest that the tube tester is not particularly sensitive to the type of defect (glass electrolysis) which caused the failure of this equipment, because it did not successfully anticipate the imminent failure of tubes. These are two examples of ineffective preventive tube maintenance that are due largely to the lack of agreement between the tube tester and the equipment application.

3.3 How Maintenance Affects Equipment Reliability

The fact that equipments change with time must be recognized. Not only do the component parts of an equipment age during operation and even during storage, but, in addition, the composition of the ages of parts can be changed drastically following a repair of the equipment. It is logical to expect the reliability of an equipment to be closely related to the condition of its component parts, and it is equally logical to expect the condition of the parts to be closely related to the age of the parts. Since older parts, failed or otherwise, can be replaced by new parts during repair, the maintenance man can exert a direct influence upon equipment reliability. Maintenance can influence future reliability not only by part replacement, but also by failure to make complete repairs; that is, by failure to remove the right parts, the maintenance man can adversely affect equipment reliability. The parts the maintenance man replaces and the time when he replaces them are two of the factors which determine equipment reliability.

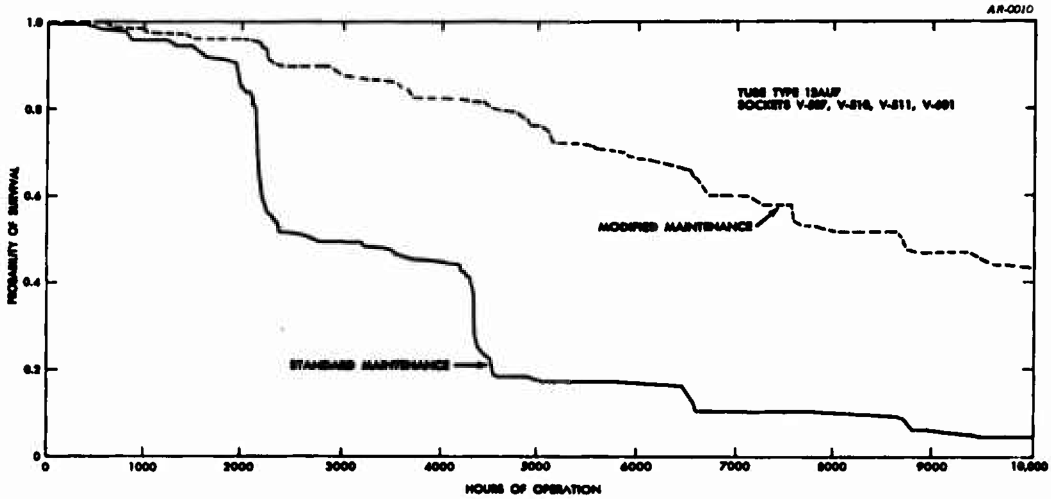


FIGURE 14
STANDARD VS. MODIFIED MAINTENANCE: OBSERVED RELIABILITY FUNCTIONS
FOR TUBE TYPE 12AU7 IN R-390/URR EQUIPMENTS

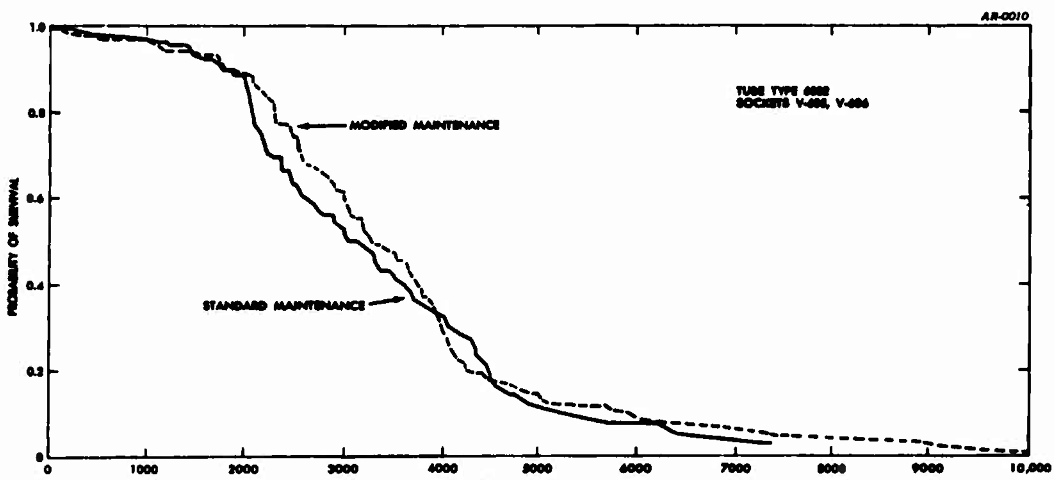


FIGURE 15
STANDARD VS. MODIFIED MAINTENANCE: OBSERVED RELIABILITY FUNCTIONS
FOR TUBE TYPE 6082 IN R-390/URR EQUIPMENTS

3.3.1 Equipment Reliability Functions

Equipment reliability functions generally are presented graphically in the same manner as are tube reliability functions. However, to plot equipment reliability in this same manner, certain assumptions must be made.

Tubes are not repaired but are thrown away upon removal; equipments generally are repaired. The time interval measured to determine tube reliability is that time from installation of the new tube until the tube is finally removed from the equipment. The time interval measured in equipment reliability functions is that time from the last repair until the next repair -- or from the last operator complaint until the next operator complaint.

If one assumes that equipment reliability functions have the same meaning as tube reliability functions, then one must make the assumption that the equipment is "good as new" following a repair. If one is unwilling to make this assumption, then the equipment reliability function must be interpreted as an average reliability function for the period of time in which the data were collected. In other words, the equipment reliability function represents the probability that the equipment will survive a given period of time from the time of any repair during the interval of observation. Reliability functions for tubes -- a throw-away item -- have only one interpretation, i. e., tube reliability functions always represent the chance of survival of a new tube.

The primary problem encountered in the preceding interpretation of equipment reliability functions is that it means equipment reliability always must be a function of the length of the observation period. When the length of the period changes, the function can change. However, it is more reasonable to interpret equipment reliability in terms of average reliability than to assume the equipments are made "good as new" following each repair. To assume the equipment is made "good as new" is illogical, because, even if the technician has corrected the malfunction, the remaining parts in the equipment are older and a little closer to the point of deterioration or failure, or both.

The reasons for presenting equipment reliability in terms of reliability functions are: (1) the presentation is simple, and (2) equipment reliability functions tend to be an almost ideal example of the theoretical reliability function,

$$R(t) = e^{-t/\theta} ,$$

where θ is the mean time-between-repairs or -complaints. Since observed equipment reliability tends to fit this model quite well, the conclusion has been drawn that the rate of equipment repair is constant, because this is the only assumption made in the theoretical model.

Unfortunately (at least from the point of view of ease of data presentation), the assumption of a constant repair rate in most instances is not correct. The rate of repair changes during different intervals of equipment life, and this change goes undetected in the observed equipment reliability functions because the time between equipment repairs loses its identity with equipment age. If the repair rate increases as the equipment ages, these shorter repair-time intervals show their effect in the early portion of the reliability function. The longer times between repairs, whether they occur at the beginning of the equipment life or in the middle of the observation period, always affect the later portion of the reliability function; thus, correspondence between equipment age and repair time is not preserved.

The manner in which equipment reliability functions are computed guarantees, in almost all practical situations, a reliability function which is J shaped. If repair rates change moderately (for example, less than 3 to 1) during the period of observation, the reliability function will be approximately exponential. A study of several different equipment reliability functions must be made before one observes that, in the early portion of the reliability graph, the observed function deviates slightly below the theoretical function, to an extent greater than would occur in sampling fluctuations. In most instances, this deviation is not sampling fluctuation affecting the data but is real evidence of a change in the repair rate of an equipment. However, it is impossible to determine from a graphical presentation whether the change occurred early or late in the life of an equipment.

Since the equipment reliability function is nearly insensitive to changes in the rate of repair, the obvious manner of presentation of repair data is in terms of repair rates for different intervals of equipment age. This is the manner in which the data are presented in this section.

3.3.2 Rate of Repair

The presentation of rates of repair for intervals of the equipment life permits a direct observation of the change in rate as a function of the age of the equipment. In this

discussion, the data relate solely to the AN/ARC-27 equipments, primarily because of the lack of a sufficient quantity of data on the other types of equipment under surveillance. The information to be considered will include, in addition to the repair rates for the AN/ARC-27 equipments, the quantities of tubes removed for the same intervals of equipment age; and, for engineering maintenance at the Norfolk Naval Air Station, the operator and/or engineer complaints registered against the AN/ARC-27 are also shown as rates. From this type of presentation -- and in particular, from the engineering data obtained at the Norfolk Naval Air Station -- several conclusions concerning maintenance can be drawn.

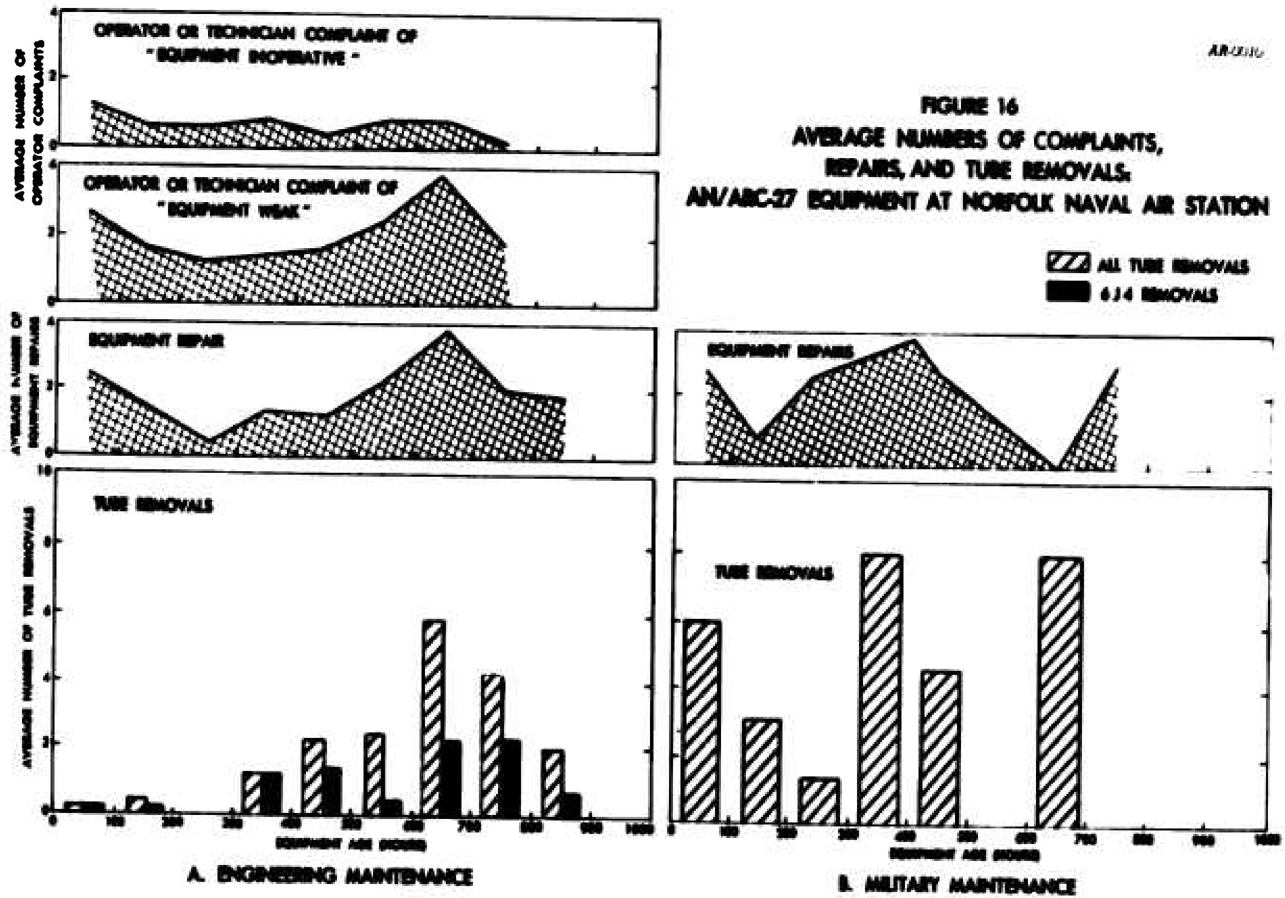
3.3.2.1 Rates for Engineering Maintenance

Figure 16, Part A, shows these various rates and the quantities of tubes removed (on a per-equipment basis) for engineering maintenance at the Norfolk Naval Air Station. It may be seen that the rate of complaint, where the complaint was of either dead or inoperative equipment, is approximately constant for 800 hours of equipment operation. Where the complaint was of weak (erratic, noisy, etc.) equipment performance, the rate of complaint is variable. The rate in this instance starts high, drops to a minimum, then rises to a peak and finally begins to fall at 800 hours. The equipment repair rate is quite similar to the rate of complaint for weak equipments. Since not all operator complaints lead to a repair, the repair rate is not quite the sum of the two complaint rates. Figure 16A also shows the average number of removals of all tube types and of the 6J4 type individually. Tube removals start low, rise to a maximum between 600 and 700 hours of operation, and then begin to fall. While the equipments under surveillance were not new at time zero, all of the tubes in the equipments were newly installed at that time.

The first point of interest is the high initial repair rate. Complaints registered against the equipment in the first 200 hours of operation were predominantly complaints of weak performance. It can therefore be assumed that repairs made in this time interval were predominantly an attempt to correct this type of malfunction. Since relatively few tubes were removed and since the tubes in the equipment were nearly new, it can be determined that defective tubes were not the cause of the complaint. However, it does not seem reasonable to blame the other parts in the equipment unduly, since they were not changed when the tubes were installed. The most reasonable explanation is that the insertion of 55 new tubes into the equipment at the initiation of the test created new

FIGURE 16

AVERAGE NUMBERS OF COMPLAINTS, REPAIRS, AND TUBE REMOVALS: AN/ARC-27 EQUIPMENT AT NORFOLK NAVAL AIR STATION



A. ENGINEERING MAINTENANCE

B. MILITARY MAINTENANCE

adjustment problems. By the end of 200 hours of operation these adjustment problems had apparently been corrected, because both the repair rate and the complaint rate for weak equipments begin to reach their minimums.

In the period from 200 to 400 hours of equipment operation, the repair rates and the complaint rates remain reasonably constant while the quantity of tube removals increases slowly. From 400 to 700 hours, the rate of complaints of weak equipments, the rate of repair, and the quantity of tube removals increase to their peaks. It seems reasonable to conclude that in this time interval tubes -- particularly the type 6J4 tubes -- became the prime cause of complaint. At the 700-hour point, over one-half of the original 6J4 tubes had been removed from the equipment and replaced by new tubes (see Figure 12). After 700 hours of operation, the repair rate, the rate of complaint, and the number of tube removals begin to drop. This abrupt change is believed to have occurred primarily as a direct consequence of the replacement of the 6J4 tubes.

Previous sections of this report have referred to the change in policy towards tube replacements by the engineer in charge of the engineering portion of the test at the Norfolk Naval Air Station. For the first 400 hours of equipment operation, the engineer restricted tube replacement to a minimum. After 400 hours he believed tubes of certain types were beginning to show signs of deterioration and thus permitted greater freedom in the removal of tubes. It is believed he was justified in making this decision. Complaints of weak equipments began to increase from 400 hours of operation until the majority of the 6J4 tubes had been replaced at 700 hours. When they were replaced, however, the complaint and repair rates began to drop. Even better equipment reliability might have been achieved had the engineer replaced <u>all</u> 6J4 tubes in the equipments at 400 hours of operation.

The preceding example of maintenance at the Norfolk Naval Air Station illustrates as clearly as is possible with this type of data the relationships among the maintenance men, tube reliability, and equipment reliability. This example is believed to be one in which only essential tube removals were made. It illustrates that (1) essential tube removals are not constant with time but increase with tube deterioration, and (2) equipment repair rates are not constant, but change with equipment age and increase particularly as tube deterioration increases. Additionally, this example suggests that "infant mortality" in equipment is neither a problem of defective tubes nor of parts, but is an adjustment problem.

In this example, note should also be made of the rate of complaint for inoperative equipments. This is the only rate that appears to remain constant. It is likely that inoperative equipments are closely associated with the catastrophic or sudden failure of tubes and other parts, and are less closely related to gradual degradation of tubes. If this supposition is correct, the rate of catastrophic tube failure also would be a constant. The rate of degradation failures of tubes, being more closely allied to complaints of weak equipment performance, will increase with equipment age as the complaint rate of weak equipment performance increases.

The proportion of complaints of inoperative equipment to total complaints also is of interest. Of the total number of complaints, only one-quarter (27 complaints) were registered against inoperative equipments, while the other three-quarters (82 complaints) were registered against weak equipment performance. This ratio of complaints suggests the magnitude of the problems of adjustment and part-deterioration in the AN/ARC-27 equipment. If these two problems could be eliminated, a fourfold increase in average time between complaints could be realized.

3.3.2.2 Rates for Military Maintenance

For military maintenance of the AN/ARC-27 equipment at Norfolk Naval Air Station, Figure 16B shows the rates of equipment repair and tube removal. The equipment repair rate is fairly high in the first 100 hours of operation, as was observed for engineering maintenance. This is understandable, since the equipments in both groups had new complements of tubes. If differences in types of maintenance do affect equipment reliability, these effects would not be particularly evident immediately after installation of new tubes.

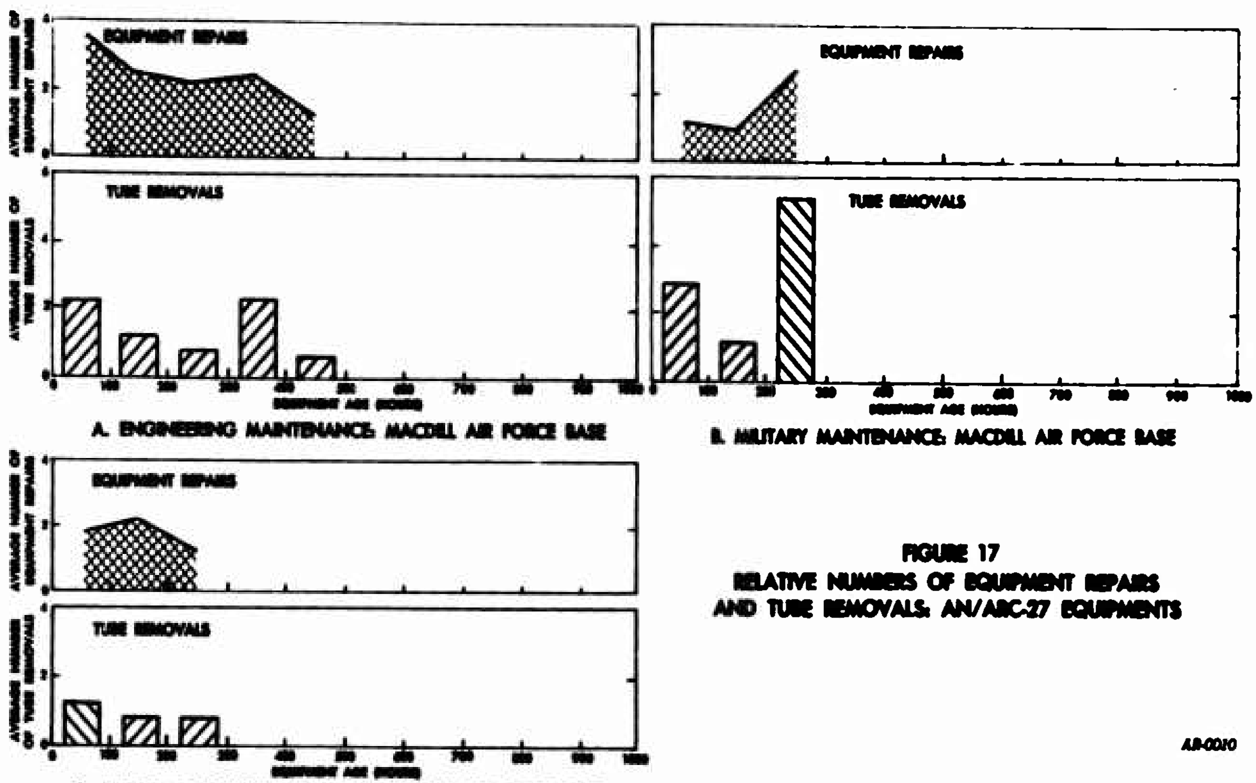
In contrast with the situation under engineering maintenance, where few tubes were removed in the first 100 hours of operation, military maintenance personnel removed many tubes. In fact, for military maintenance, the rate of tube removal tends to parallel the rate of equipment repair throughout the entire period of the test. This, again, is evidence of the extent to which most military maintenance men accept the idea that tubes are the major cause of equipment malfunction and, also, the extent to which they rely on trial-and-error tube replacement. Figures 16A and 16B indicate that, under military maintenance, it is a matter of equipment failure determining tube removal rather than tube failure determining equipment failure.

The major point of difference in the rates of military and engineering equipment repair is that the rate for the military peaks earlier -- between 300 and 400 hours. Explanations must be somewhat speculative, but it may be reasonable to assume the military technicians were not correcting the basic cause of malfunction. In the 0- to 500-hour interval, most engineering repairs were made by adjustments, while most military repairs included replacement of tubes. It seems likely that adjustments or realignments were the needed repair actions, but that tube substitution could have compensated somewhat for the needed realignment (or tube substitution might have aggravated the infant-mortality effect by creating the need for more adjustments). The military technicians removed many more 6J4 tubes than did the engineers in the process of tube substitution during the early part of the test. This tube type is commonly suspected by the military. As a consequence of the "premature" removal of these tubes, 6J4 failures did not occur several hundred hours later, as was observed in the case of engineering maintenance. This, then, may account for the drop in the rate of equipment repair at 500 to 600 hours of operation.

If the foregoing explanation is valid -- and it is so considered by ARINC Research Corporation, at least in the major lines of the argument -- maintenance men can, and do, alter equipment reliability adversely by their failure to repair the real cause of equipment malfunction; and they alter it beneficially by inadvertently performing preventive maintenance by replacing tubes. This suggests that, if maintenance is conducted on a more logical basis, reliability of equipments can be improved and removal of tubes can be reduced.

3.3.2.3 Engineering vs. Military Rates, Air Force Bases

The charts in Figure 17A illustrate the results of engineering maintenance of AN/ARC-27 equipments at MacDill Air Force Base. The equipment repair rate is not appreciably different from that for engineering maintenance at Norfolk Naval Air Station (see Figure 16A) -- a fact which again suggests that installation of new tubes caused a somewhat higher rate of initial repair. The engineers at MacDill Air Force Base tended to remove more tubes than did the engineers at Norfolk Naval Air Station. It is quite probable that some differences in attitude toward tube removal existed within the engineering groups. However, it was also found that a particularly poor lot of tubes had been installed at MacDill Air Force Base; thus, the initially high tube removal rate may have represented a weeding-out process.



A. ENGINEERING MAINTENANCE: MACDILL AIR FORCE BASE

B. MILITARY MAINTENANCE: MACDILL AIR FORCE BASE

C. ENGINEERING MAINTENANCE: CARSWELL AIR FORCE BASE

FIGURE 17
RELATIVE NUMBERS OF EQUIPMENT REPAIRS
AND TUBE REMOVALS: AN/ARC-27 EQUIPMENTS

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The results of military maintenance at MacDill Air Force Base are shown in Figure 17B. More tubes were removed than under engineering maintenance; and, as occurred under military maintenance at Norfolk Naval Air Station, tube removals tend to follow the equipment repair pattern with time. The repair pattern does seem to deviate from the previous examples, where a type of "infant mortality" has been observed. The only explanation for this deviation is that the observed data are very limited and may not be sufficient to illustrate more than a possible trend of maintenance.

Figure 17C shows the results of engineering maintenance at Carswell Air Force Base. Here, again, the results are extremely limited, but the initial equipment-repair rate seems to be falling off and tube removals are quite low, although they are somewhat higher than for engineering maintenance at Norfolk Naval Air Station. No graph has been prepared for military maintenance at Carswell Air Force Base because it was believed the data were too limited.

3.4 Summary for all Types of Equipment in Test

Since the data on the other types of equipment in the test are more limited than the AN/ARC-27 data, only a summary analysis will be presented to illustrate the effect of maintenance upon the reliability of these other equipments. Table 19 shows the mean time between operator complaints and the mean time between repairs for each equipment type and each maintenance group under surveillance. A table such as this, of necessity, leaves much unsaid; however, several features are worthy of comment:

(1) There is considerable variability in the average-time data, although a closer scrutiny of these data does show that equipment types are reasonably well characterized.

(2) When complaint and repair times for similar types of equipment are compared between bases, the effects of the individual bases upon maintenance become apparent. It is likely that the differences attributed to the bases are caused by the different lengths of time the equipments are used -- for example, by reason of the differences in the length of the mission.

(3) If the time-data in Table 19 are compared with the number of tube sockets in each equipment type, some negative correlation can be found -- i. e., as the number of sockets increases, the time between

TABLE 19

SUMMARY OF REPAIR DATA FOR ALL TYPES OF EQUIPMENT IN TEST

Equipment Type (No. of sockets in parentheses)		Test Base*	Mean Time-Between-Operator-Complaints		Mean Time-Between-Repairs	
			Military	Engineer	Military	Engineer
AN/ARC-27	(55)	CAFB MAFB NNAS	183 77 32	56 77 52	106 48 46	69 64 56
K-System	(233) (237)	CAFB MAFB	19 12	23 10	18 11	23 10
AN/ARN-14	(R-252B) (R-252B) (25) (R-540)	CAFB MAFB MAFB	165 ** 228	62 34 99	120 ** 183	108 39 99
AN/APS-31	(159)	NNAS	7	9	10	13
AN/APS-38A	(209)	NNAS	9	14	9	14
AN/URR-13B	(23)	N(Ship)	4200	2243	2673	805
TED-3	(16)	N(Ship)	396	678	263	293
AN/PRC-6	(13)	Infantry, EUCOM	†	†	46	36
AN/PRC-10	(11)	Infantry, EUCOM	†	†	206	238
AN/GRC-4	(56)	Armored, EUCOM	†	†	60	82

*Legend

CAFB - Carswell Air Force Base
MAFB - MacDill Air Force Base
NNAS - Norfolk Naval Air Station
N(Ships) - Norfolk Naval Station (Ships)

Infantry, EUCOM
Armored, EUCOM
Infantry and Armored divisions at Wurzburg and Bad Kreusnach, Germany, respectively

** No operator complaints or repairs.

† No estimate available.

operator complaints or the time between repairs tends to decrease. This verifies the observation that equipment reliability is a function of the number of tubes, among other things.

(4) Finally, it is apparent from Table 19 that mean time between operator complaints and mean time between repairs are somewhat insensitive indexes of the differences in the maintenance groups. These time data furnish very little evidence of the superiority of one group over another. A more sensitive measure of the quality of maintenance would be either time required for repair or quantity of parts removed.

4. EVALUATION OF FINDINGS

The preceding sections of this report have pointed out some of the external factors beyond the general control of maintenance, and some of the effects these factors exert upon maintenance. Also discussed have been the maintenance man's approach to repair and the effect that his approach and other maintenance factors can have upon tube and equipment reliability. In this section, an evaluation of these various factors and suggestions for improvement of maintenance practices in the field of military electronic equipments will be presented.

4.1 Tubes as A Maintenance Problem

By means of the control of maintenance exercised in this test, it has been possible to isolate some of the relationships among tubes, equipment reliability, and maintenance. It seems apparent that tubes are less of an equipment problem than might be suspected on the basis of tube-removal data obtained in the past. While more tubes generally are removed than is necessary, there also has been a failure to remove the right types of tubes before they cause equipment malfunctions. The problem of gradual tube wear-out, while known to exist, has generally not been described by adequate statistical data. It seems apparent that if tube wear-out failures can be eliminated, either by replacement of the tube prior to actual failure or by elimination of the causes of wear-out equipment reliability can be improved. For example, ARINC Research Corporation has conducted experiments on the AN/ARC-27 equipment in which the filament voltages applied to the type 6J4 tubes have been reduced in an attempt to alleviate one of the sources of tube wear-out. The results of this experiment indicate that, by voltage reduction, the useful life of the 6J4 tubes in the equipment can be prolonged by several hundred hours.

Under normal military maintenance conditions, the tube-equipment reliability relationship is difficult if not impossible to appraise. The problem seems to stem from the usual tendency in military maintenance to blame tubes unduly for many equipment failures and the resulting practice of removing tubes in large quantities. In fact, it seems almost

truer to say that tubes are removed because of equipment failures than to say that equipments fail because of tube failures.

On the other hand, indiscriminate tube replacements can exert a slightly beneficial effect upon equipment reliability. Inadvertent removal of some of the potential wear-out failures before they actually cause trouble in the equipment may have the effect of reducing equipment failure rates. This effect is probably slight; for unless tube replacements are systematic, there is probably a considerable chance that many of the potential wear-out failures will be undetected until they have caused an equipment failure.

It would be desirable to use the information and findings in this report to arrive at a logical maintenance procedure which would maximize equipment reliability and, at the same time, keep needless tube replacements to a minimum. However, it is questionable whether or not a single approach would have universal application. The following requirements seem apparent:

(1) Information on the times of tube wear-out should be collected. The data presented on the AN/ARC-27 equipment is only valid to about 900 hours of operation. During this time, a majority of the type 6J4 tubes begin to show evidence of serious wear-out. However, information on wear-out time of other tube types in the AN/ARC-27 equipment is not available. Possibly an extended controlled test would be the only means of obtaining this information.

(2) Maintenance would have to be more discriminate in the matter of tube removals at repair. It would be of no benefit to advocate a preventive maintenance procedure that consisted of tube replacements at fixed times if tube replacement had already occurred in the course of normal repair.

(3) It would be necessary to develop techniques by which a reasonably accurate record could be kept of the time accumulated on each equipment. (Inexpensive timing devices which might be acceptable are available.)

If maximizing equipment and tube reliability by improved maintenance procedures is to be the goal, then all of the above-mentioned conditions would have to prevail. In the practical situation, achievement of this situation might be

quite difficult. The value of the gain should be considered against the costs of achieving the gains. Whether or not the gain in equipment reliability and the reduction in tube replacements would be worth while would be dependent on the specific application.*

4.2 The Maintenance Organization

In Section 2 of this report, the structure of several different types of maintenance organizations was discussed. Generally, it was concluded that most maintenance organizations would have to be -- and, in fact, were -- built around the tactical requirements of equipment availability. Furthermore, the operational needs dictated special requirements. Thus, the maintenance organization for aircraft electronic equipment is a centrally located ground maintenance station capable of performing almost all types of maintenance, from the very simple to the most complex. Shipboard electronic equipments, on the other hand, require a self-contained maintenance facility aboard ship, able to perform any level of maintenance. The equipment mobility requirements in the Army dictate a maintenance organization that consists of several repair stations, and equipments needing repair proceed sequentially through these stations until they reach a level of maintenance skill capable of completing the required work.

The comparison between military maintenance organizations and the corresponding engineering maintenance organizations indicates, on the surface, that considerable simplification and increased effectiveness in the military structure could be achieved. It would not be realistic, however, to make recommendations for change solely on the basis of this study and without further consideration of the individual situations. Simplification of maintenance organization is an area worthy of study.

It was demonstrated by the engineers in this test that fewer men (assumed to be better trained) could do an equivalent or superior maintenance job. However, it is not necessarily feasible to reduce the military maintenance organizations numerically to the level of the engineering groups, because some additional men should be provided for emergencies, and also, some men should be assigned to maintenance primarily for the purpose of on-the-job training. It should not be assumed, on the other hand, that the present structure of maintenance organizations is necessarily good because it has been adequate in the past. New equipments change the maintenance problems. There is a need to re-evaluate the adequacy

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* See Monograph No. 7, cited in footnote on page 76

of the organization to meet the demands of the new equipment. The task is essentially one of determining the level of maintenance training and the type of test facilities that are required for adequate maintenance of the equipment.

In the Army, one of the serious problems seems to be lengthy delay times. A substantial reduction in delay times would be equivalent to having more spare equipments for tactical usage. Paradoxical as it may seem, the indications are that fewer maintenance technicians -- rather than more of them -- would reduce delay time in equipment repair.

It appears likely, also, that fewer maintenance men would be required if the military were to eliminate a certain amount of specialization in the maintenance job. Such a change might be effected, for example, by giving a maintenance man responsibility for a whole equipment or for several different types of equipment, rather than for only a certain part of a single equipment. If this were done, of course, maintenance men would require broader training.

The efficiency of maintenance could be materially improved by making available an adequate supply of spare equipments and parts. If adequate spares are on hand, equipment availability can be maintained at a fairly high level. However, an adequate supply of spare equipments will not by itself necessarily reduce over-all maintenance manpower requirements. Temporarily, spares reduce the amount of excessive manpower required to meet an emergency; but, in the long run, failed equipments must be repaired when the spares are exhausted. The advantage of having an adequate number of spare equipments is that the additional spares permit a more even distribution of the workload, which in turn makes possible better utilization of maintenance time and reduction of the number of men required to meet an emergency.

Several general recommendations for the improvement of the attitude of maintenance men also deserve mention. One recommendation, which was suggested by some of the military men participating in this test, is to make provisions for better on-the-job training. Another recommended measure, which obviously would not be easy to accomplish, is to train the maintenance men to a higher level. Still others are: (a) reduce the pressure on the maintenance man to make hasty repairs, but at the same time provide a workload sufficient to keep him usefully occupied and interested; (b) assure that test facilities are adequate; (c) try to achieve more stability by reducing personnel turnover; (d) improve equipment design for maintenance, and (e) improve test equipment used in isolation of equipment malfunctions.

Efforts toward improvement should not overlook the influence of the equipment operator on maintenance. Substantial gains in both reliability and maintenance efficiency might be achieved if the operator were better trained and if the equipment were designed for ease of operator use.

4.3 Evaluation of Equipment Maintenance

In this report, it has been assumed that the primary maintenance objective was to keep equipment availability at the highest level possible. This can be accomplished in any or all of the following three ways:

(1) increase the spare equipments,

(2) prevent foreseeable equipment failures, and

(3) correct equipment failures quickly.

If one assumes that good maintenance achieves high equipment availability, while at the same time minimizing maintenance effort and quantities of spare parts used, the following recommendations can be made:

(1) Improve preventive maintenance, and

(2) Improve corrective maintenance.

These recommendations will be discussed in Sections 4.3.1 and 4.3.2.

4.3.1 Improvement of Preventive Maintenance

Preventive maintenance has two general purposes: (1) to eliminate existing failures prior to equipment use, and (2) to prevent foreseeable equipment failures.

The first type of function -- to eliminate existing failures prior to equipment use -- has sometimes been called routine maintenance. The success of routine maintenance depends upon the regularity with which it is performed; however, the frequency of equipment checks should be considered cautiously. Apparently there is as much of a tendency to make the checks too frequently as to make them too infrequently. For example, in the Navy shipboard segment of the test, the Navy technicians often failed to make periodic checks of the equipment because of the pressure of other duties. On the other hand, the engineer in the same part of the test rigorously followed a schedule of weekly equipment checks. In time, the engineer expressed the opinion that

some of these checks were useless, and subsequently he eliminated them from his procedure without detrimental effect on reliability. The engineering maintenance groups in both the air and ground force segments of the equipment in many instances favored frequent scheduled checks of equipment. These groups reported that in many instances equipment failures were detected during routine checks. Undoubtedly, some of these checks eliminated subsequent complaints by the equipment operator.

The second function of preventive maintenance -- to detect and eliminate foreseeable failures -- seems to have been misapplied in current maintenance practices. Preventive maintenance is performed either to excess or not at all. This is not surprising considering the paucity of deterioration data available to the maintenance man and the lack of adequate test equipment designed to detect incipient failures. Data presented in this report demonstrate that certain tube types -- for example, the 6J4WA -- do exhibit strong wear-out characteristics. The wear-out failures tend to occur at the same time; thus, it is possible, where sufficient data are available, to eliminate the seriousness of wear-out tube failures by removal of these tubes at preselected times. Not only would this procedure tend to improve equipment reliability, it should also ease the maintenance burden in that fewer corrective repairs would be necessary. Before this type of preventive maintenance can become practicable, sufficient tube-life information must be available and means must be devised for recording the accumulation of operational hours for equipments.

4.3.2 Improvement of Corrective Maintenance

Throughout this report, emphasis has been placed upon the basic trial-and-error nature of almost all approaches used in corrective maintenance. That is, if the cause of an equipment malfunction is not obvious, there is always the chance that an error will be made when the cause of malfunction is corrected, regardless of the maintenance approach used.

When the importance of trial and error in performing corrective maintenance is assumed, it would seem that the preferred repair procedure would be to start at the system level and first isolate the malfunctioning subsystem. The next step would be to identify the malfunctioning part. An approach such as this should, in the long run, minimize both the time spent in maintenance and the number of parts needlessly removed. It most quickly eliminates the parts of the

system which are functioning correctly and permits concentration on those portions which may contain the cause of malfunction.

Unfortunately, one of the common observations made during the ARINC Research test was that the military maintenance man, when under pressure or when he lacked experience, tended to reverse the procedure outlined above. Frequently, the military maintenance man would initiate repair at the tube level and would resort to mass tube substitution in an attempt to isolate and correct the cause of malfunction. This procedure -- direct part replacement -- is essentially inefficient and time-consuming, since there are many parts which could be the cause of equipment failure.

If the technique of analysis from the system level to the part level is to be successfully applied, emphasis must be placed upon this method during training. It is important that the maintenance man be trained both to recognize symptoms of equipment malfunction and to logically develop hypotheses as to the possible causes of malfunctions. One further requirement for the success of this method is that the maintenance man must have good test equipment available for his use.

The data in this report demonstrate that the majority of equipment complaints are the result of marginal equipment performance rather than of inoperative equipment. This observation suggests that many of the repairs could be accomplished by adjustment and realignment of the equipment. For example, as illustrated in Table 8 (page 59), the engineers were able to repair approximately one-third of the AN/ARC-27 equipments by adjustments alone.

Part replacements might be minimized by the following sequence of maintenance actions at a corrective repair: First, try to repair the equipment by making only adjustments or realignments. Second, if the equipment is not repaired by adjustment or realignment, try to isolate the cause of malfunction to a tube. (Isolation of malfunctioning tubes by substitution of a known good tube is preferable to reliance upon the results of a tube tester.) Third, if neither adjustments nor tube replacements correct the malfunction, try to isolate the trouble to parts other than tubes.

The sequence of action outlined above should reduce needless tube replacements and, in addition, it has the possible advantage of saving time in that it proceeds from the easiest maintenance action -- and the one which is the most common cause of equipment failure -- to the action which

is most difficult or time-consuming and the one least likely to be the cause of the malfunction.

In some maintenance situations, tubes may be considered relatively inexpensive with respect to either the cost of an equipment failure or the cost of maintenance. In these instances, it may not pay to attempt to obtain maximum life from a tube. For example, if maintenance were to be performed at a remote site, entailing high travel costs -- and if the cost of an equipment failure is also high -- then one would not attempt to maximize tube life. In this case, an approach which might be used at corrective maintenance would be to remove and test all tubes on a tube tester. Those tubes which were obviously defective or were marginal would be discarded and replaced by known good tubes. This type of procedure effectively does two things: First, it performs preventive maintenance in that potential tube failures are eliminated, thus minimizing the chance of a call-back; and, second, it eliminates tubes as a possible cause of failure of the particular equipment. If tube replacement does not restore the equipment to operating condition, the maintenance man must try to repair it by adjustment or replacement of other parts.

One technique which would seem to materially aid the maintenance man at corrective repairs would be to keep adequate equipment records. These records should both specify the symptom of each equipment malfunction and list the parts which were removed at repair. In addition, it would be desirable to record the time (accrued operating hours) at which each malfunction occurred. Records such as this would aid in location of the particular source of a frequently recurring symptom. They would materially shorten maintenance time and provide an efficient means whereby the experience of one man or group of maintenance men could be transferred to another man or group.

4.4 Recommendations for Equipment Design

It is not an objective of this report to explore or to duplicate the excellent literature which already exists concerning human engineering in equipment development. This literature makes recommendations on equipment design for both ease of equipment operation and maintenance. A point which merits emphasis, however, is that the use of human engineering in equipment design, from the aspect of the operator of the equipment, may make the maintenance job easier by eliminating some of the operator complaints that stem primarily from difficulty in operating the equipment.

In this section, some of the topics the human engineer might consider in the design of new equipment are emphasized. Of major importance are the manner in which the equipment will be used and the maintenance facilities and procedures available in the field. For most new equipment, it is more reasonable to design the equipment around the existing user than to design an equipment which will require extensive retraining of the using personnel.

Several levels of repair are basic in the structure of most field maintenance organizations -- for example, the flight-line and the shop maintenance in the Air Force, and the company, battalion, regiment, and signal repair team in the Army. A radio that is intended for use by the Army in all likelihood should be designed differently, from the maintenance point of view, from a similar radio to be used by the Air Force.

If one adopts the general principle that a repair should proceed from the system level to the part level, then one must recognize the differences in the meanings of "system" and "part" for each level of maintenance. On the flight line, the objective of the maintenance man is to confirm the fact that the system is malfunctioning, and then to identify the defective unit for removal to the shop. In the shop, the maintenance man's objective is to confirm that the unit is defective, and then to identify the defective assembly and part. The equipment designer, keeping these objectives in mind, can ease the maintenance burden considerably if: (1) he specifies proper test procedures and furnishes proper test equipment to isolate the malfunctioning component; and (2) he makes each of these sub-units readily accessible to the maintenance man.

The design engineer can ease the maintenance burden in another way -- although, generally speaking, this has not been considered at any great length in human engineering literature -- by designing a system with greater tolerances. This not only would make the equipment more reliable, it also would eliminate the need to make many of the minor adjustments that now plague maintenance.

Currently, considerable emphasis is being placed upon the concepts of modular construction of equipments and the use of "throw-away" units. The usual arguments favoring these concepts are that they simplify maintenance jobs and, if correctly designed, reduce the cost of maintenance. If modules are to be considered in the design of a new equipment, the following principles should be kept in mind:

(1) Parts used in a specific module should, insofar as possible, contribute to a single function. Modules so designed should be relatively independent of each other in the sense that, if one module fails, it will not cause the failure of another. If this principle is adhered to, the maintenance task of isolating the malfunctioning module is simplified -- that is, it is less time-consuming to isolate a trouble to a single module than to identify several modules which are the cause of a failure.

(2) In modular construction, standard modules should be used as much as possible. This policy simplifies the maintenance job, since the maintenance man needs to understand only a relatively few types of modules; it reduces the amount of test equipment required; and it simplifies the logistic problems by requiring that only a limited number of different types of modules be supplied for repair purposes.

(3) The individual modules should be small enough to be handled easily by the maintenance man, and they should be readily accessible and easily disconnected from the system.

(4) If a module is to be thrown away rather than repaired, then, in the interest of economy, it is advisable not to mix expensive and inexpensive parts within the same unit -- thus, the expensive part will not be thrown away as a result of a failure of an inexpensive part. It also is desirable that the life expectancies of all parts within a unit be of the same order of magnitude, so that a short-lived part will not require the loss of longer-lived parts.

Much of the success of modular design will depend upon good cost information and upon reasonably accurate information regarding life expectancies of parts. Reasonably good part-life data, under a variety of different environmental conditions, is now becoming available. Even if modular construction is not used for a particular application, it is well to consider part-life expectancies to insure that short-lived parts are made the most accessible to maintenance. It also would be of value if maintenance manuals made use of this information to outline a program for preventive maintenance.

4.5 The Need for More Maintenance Studies

Throughout this report, certain maintenance problems have been considered in a fairly general way, and some principles that can lead to easier maintenance and increased equipment reliability have been stated. However, it has been stressed that one course of action under one set of conditions may not be an acceptable course of action under another set of conditions. Each specific problem should be considered individually. It would seem that sufficient information is now available to permit development of specific procedures for various maintenance situations. ARINC Research Corporation recommends that more effort be placed on studies directed toward that objective, since the potential pay-off in economy of maintenance is considerable. A definite need exists, also, for continued field studies with emphasis placed on the accumulation of more part-life data and on the study of existing maintenance procedures within the framework of the maintenance organization.